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Extended Abstracts

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Extended Abstract 3

Title
Design Enabler to Recognize Duplicate Geometries in CAD Assemblies
Extended Abstract 3

Title
Design Enabler to Recognize Duplicate Geometries in CAD Assemblies

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Keywords
Feature Recognition, Duplicate Geometry, Similarity

Introduction
This paper presents a method for identifying components in CAD assemblies that have surfaces that have complementary, duplicate surfaces. This method can be used for applications such as identifying potential lazy parts, a previously developed method used by an automotive OEM [3], and generating connectivity graphs for use in manufacturing assembly time estimation [2]. This paper presents the algorithm, a justification, and example test cases and scenarios that demonstrate its utility.

Main Idea
Duplicate geometry is one of the seven indicators of the lazy parts mass reduction method [1]. The lazy parts method is a light weight engineering method that is used for analyzing parts with the mass reduction potential. The duplicate geometry is defined as any geometries lying equal to or within the threshold distance with the user-defined orientation between them and have the percentage similarity that is equal to or greater than the threshold value. The feature recognition [5, 6] system developed in this research for the identification of duplicate geometries is also extended to retrieve the weighted bipartite graph of part connections for the assembly time estimation. The weighted bipartite graph can be used as input for the part connectivity based assembly time estimation method [4].

A formal definition for duplicate geometry is first offered. In order to remove the ambiguity involved with identifying duplicate geometry from the current definition and also to make the definition objective for the purposes of automation, the following definition is proposed: Geometries lying equal to or within a threshold distance (user defined) with the surface outward normals opposed to each other within a threshold tolerance (user defined) and the percentage of similarity between the two geometries is equal to or within a threshold value (user defined). In this definition, there are three user defined variables that determine if the geometries are duplicate: allowable threshold distance (how far apart are the parts in the assembly), allowable orientation (how aligned are the surface normal of the compared sampling points), and degree of overlap (the accepted percentage of overlap of two compared faces).

The SolidWorks API software development kit is used in this research to develop a feature recognition system in SolidWorks CAD software package using C++ programming language. The feature recognition system is built in the SolidWorks CAD software using a combination of topology and geometric data for the evaluation of duplicate geometry. Distances between sampling points are used to determine proximity of surfaces. The feature recognition algorithm has three phases of evaluation. First, threshold distance condition of parts in the CAD assembly are evaluated. Second, the part pairs that have met the threshold distance condition are evaluated for the orientation. The threshold distance and orientation are the necessary but not the sufficient conditions for duplicate geometries. In the third phase, the geometries that have satisfied orientation condition are evaluated for the degree of overlap. This algorithm is illustrated in Figure 1.

Several test cases are used to validate the algorithm against the requirements list. The test cases are designed to check the performance of the algorithm for the evaluation of the threshold distance, orientation, and percentage similarity condition. Figure 2 illustrates results from the implemented design enabler applied against an assembly model of a motor mount. The results indicate that the duplicate geometry algorithm is able to successfully conduct all the three phases of evaluation. The algorithm is independent of the geometric type and is able to analyze planar, cylindrical, conical, spherical, freeform, and toroidal shapes. The number of sampling points generated on the faces of parts for the orientation and percentage similarity evaluation has the significant effect on the analysis time. The worst case complexity of the algorithm is $O\left(N \times F^2 \times F^2 \times P^4\right)$, where $N$ is the number of parts in the assembly, $F$ is the number of faces in the parts that meet the threshold distance condition, $F^2$ is the number of faces that meet the orientation condition, and $P$ is the number of sampling points on the face.
Conclusions

The duplicate geometry feature recognition approach is used to demonstrate the applicability in the extraction of assembly relations for the part connectivity based assembly time estimation method. The algorithm is also able to extract part connectivity information for the patterns. Further research is required to automate the identification of other laziness indicators in order to make the lazy parts method a completely automated tool. With regards to the complete automation of part connectivity based assembly time estimation method, the duplicate geometry feature recognition system needs integration with the algorithm for the computation of bipartite graph of part connections for the prediction of assembly time.

References


Extended Abstract 4

Title
Question/answer techniques within CAD environments: an investigation about the most effective interfaces

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Keywords
Question/answer, CAD systems, design fixation, pictorial communication, problem solving

Introduction
A noticeable quantity of contributions addresses the need of CAD systems to better support the initial phases of engineering design cycles. Within these steps, less oriented to the optimization of the virtual model of a new product, the reasoning of designers plays a major role in defining the main features of the project and the layout of a solution.

In previous works scholars have highlighted the potential benefits of computer-aided coaching systems capable to assist the designer during the definition of product concepts and embodiments [1, 2]. Experiments have been conducted by using trivial question/answer systems and algorithms resulting in positive, but not fully satisfying outcomes [3]. Many cases demonstrate how a not marginal amount of mistakes or misunderstandings of the users can be ascribed to design fixation, frustration or feelings of boredom.

Main Idea
The future versions of question/answer frameworks implemented in CAD environments require fundamental modifications in terms of improving their efficacy by marginalizing the potential emergence of problems affecting the design discourse and the human thinking. In this sense the authors have analyzed the literature in order to individuate potential strategies to overcome the current limitations. In a first instance, the paper discusses, on the basis of literature evidences, why fixation and boredom are deemed to tremendously impact the outcomes of CAD applications in the initial part of the design process [4]. In the remainder of the paper, a survey is conducted to evaluate which tools could be employed in the question/answer interface to enhance the effectiveness of human-machine interaction. More in details, the authors have analyzed previous contributions discussing the proficiency of introducing images, sketches, computer agents, vocal communication replacing written text.

More in detail, many systems integrate pictorial communication in order to enhance their capabilities. Won [5] assesses the relevant role played by sketches and visual thinking as a support of Computer Aided Design systems. Kokotovich [6] demonstrates the utility of schematic representations in a graphical format, such as non-hierarchical mind maps, in engineering design. His survey shows how such instruments represent a valid aid since they allow designers to “see” simultaneously both the big picture and the investigated details of the project. With the aim of favoring the employment of pictorial communication means in chat bots, Pirrone et al. [7] build and test a system for both text-based and graphical interaction between man and machine. While the efficacy of embodied computer agents is doubtful [8], technologies implementing oral conversation are not sufficiently mature to replace written text in dialogue systems [9].

The main emergence from the literature stands in very differentiated preferences for design interfaces according to single users. The results provided by Brunett et al. [10] highlight the different approaches by females and males in employing computer systems for problem solving. Taking into account the diversities between the genders is particularly relevant in design, given the different behaviors observed within engineering and technology followed by males and females, as recently documented in [11]. However, the approaches followed by designers do not differ just with regards to their sex and computer aptitude. In order to better serve the needs of collaborative design environments, Doulamis et al. [12] started to develop a versatile computer framework that adapts its behavior according to the kind of user, as revealed by a system working through Artificial Neural Networks. With respect to the main aim of the research, examples of customizable dialogue-based instruments are, on the other hand, scarcely diffused [13].
Conclusions
The survey suggests that variegated instruments can result suitable for different kinds of users, according to their experience in design, gender and orientation towards approaching problem solving tasks.

References
Extended Abstract 5

Title
Prosthesis socket design through Shape Optimization

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Keywords
Shape Optimization, CAD, CAE, Prosthesis Design

Introduction
The socket is an important element of the prosthesis, which accomplishes the function of supporting the residual limb of the amputee during the standing phase and the gait cycle. Design and manufacturing of sockets are hard activities due to the several functional and ergonomic requirements that should be fulfilled. Moreover, the development of the socket is a handmade process performed by skilled technicians, that requires not negligible efforts and results very time consuming. In the last years many research works have been carried out with the aim of finding alternative ways for developing prosthesis without time consuming activities and with a minor involvement of the patient. Digital models of the human body and several virtual prototyping techniques have been integrated in the socket development process trying to accomplish the just recalled objectives. In [1] a first integration of CAD with FEA for socket design purpose has been presented. Here CAD tools are used to obtain a first design of the socket according to the limb anatomy, and FEM are used to verify the socket fitting. A similar framework based on the integration of RP techniques and CAE tools is described also in [2]. In [3] an approach to assist orthopedic technicians is depicted: it uses virtual prototyping and digital human modeling to design the socket and simulate its behavior. All such kinds of methodologies have led to relevant improvements of the socket development process in terms of costs and patient involvement. However, even thought virtual prototyping techniques have allowed to drastically decrease the use of physical prototypes as well as the number of experimental tests on patient, optimization cycles are still time-consuming since they may involve several iterations. Starting from these premises, the paper describes an approach to design socket prosthesis, which is based on the adoption of Shape Optimization as means to speed-up the overall development process.

Main Idea
The use of design optimization could represent an interesting solution to address the just recalled problem. Design Optimization is rather common in several engineering fields since 80’s and Shape Optimization has been more and more adopted during the last years as useful tool to assist designers in searching for optimal solutions dedicated to prosthetic systems. For instance, in [4] a procedure for structural shape optimization of short reinforcement fibers using finite element analyses has been presented. More recently, in [5] a method for numerical shape optimization, which minimizes interface stresses, has been applied to design artificial joints. Starting from this evidences, the paper investigates the implementation issues related to a design process (Fig. 1) of the socket based on the usage of Shape Optimization. The functional and ergonomic requirements that the socket should fulfill are analyzed in order to define objectives and constraints of the optimization process. The outputs of this analysis are used to set up the optimization task, i.e. objective function, design variables and constraints. Eventually, the parameterization strategy (Fig. 2) of the virtual prototype representing the socket is investigated with the aim of identifying the basic features of a physics-based model not only capable to simulate the mechanical interactions but also easy to be managed by the optimization. To this aim, the integration issues of the employed CAD and CAE tools within the optimization process are also treated, as well as the implementation of the whole optimization process.

Conclusions
The proposed approach has demonstrated its capability to improve the design process of the socket prosthesis since it can speed-up the involved optimization activities that are still performed by hands. However, it seems expensive in terms of computational resources, therefore further investigations are required in order to identify possible remedies aimed at decreasing the computational efforts and preserving the demonstrated efficiency.
Acronyms
CAE – Computer-Aided Engineering
CAD– Computer-Aided Design
FEA – Finite Element Analysis
FEM – Finite Element Method
RP – Rapid Prototyping

References

Figure 1: Shape optimization process to assist the development of prosthesis socket.

Figure 2: Parameterization of the surface of the socket.
Extended Abstract 6

Title
Local-Global Image Binarization for Reconstructing the Cellular Structure of Polymer Foam Materials

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Keyword
Cellular Structure, Reconstruction, Engineering Materials, Image Binarization

Introduction
This paper presents a new hybrid method for the adaptive binarization of cellular structures. The proposed method incorporates two established binarization methods, one global approach and one local. The binarization of cellular structures presents particular challenges as images often include distinctive edges that exist at different depths. This issue is addressed along with the common problems of noise and gradients that can be present in images. By incorporating global information with the local information, the current method was able to maintain the details achieved by the local method while reducing the noise as a global method does. Experimental results indicate the efficacy of our approach in comparison with existing methods.

Main Idea
Our test cases first underwent binarization by way of a variety of global and local thresholding methods. This was done using ImageJ (http://rsb.info.nih.gov/ij/), an open-source image processing program. Each algorithm was coded by Landini [1] and implemented as a plugin for the ImageJ software. Global methods tested included Huang and Wang’s fuzzy thresholding method (Huang & Wang, 1995), Li and Tam’s Minimum Cross Entropy thresholding [2], Otsu’s method [3], and Yen et. al.’s multilevel thresholding [4]. The local methods explored were the Niblack [5] and Bernsen [6] algorithms. From these results we selected the single best global and the single best local algorithm to be utilized in the hybrid approach. By inspection it was determined that Niblack’s local method captured the most cell walls among the local approaches, while Huang’s global approach captured the most cell walls while containing minimal noise across all test cases.

In order to utilize the information from both the Huang and Niblack methods, we first obtain the binarization results from both methods. Determining the best method (\(B_n\)) to use in determining whether a given pixel is part of a cell wall or part of the background we use the standard deviation of the gray-levels in the images:

\[
B_n = \begin{cases} 
\text{Niblack, if } |\text{Niblack-Huang}| > 2\sigma \\
\text{Huang, Otherwise}
\end{cases}
\]

where Niblack and Huang represent the pixel binarization produced by the Niblack and Huang methods, respectively. \(B_n\) is the pixel binarization of our hybrid method and \(\sigma\) refers to the standard deviation of image gray levels.

We decided upon this determination due to the potential presence of large gradients or varied luminosities in a given image. In cases where there is a large variance in the gray-levels in an image, local methodologies tend to perform well whereas global approaches tend to calculate large portions of the given image to be a part of the background. Using this knowledge we decided to utilize the absolute value of the difference of the Huang and Niblack results as a heuristic for determining whether the pixel under evaluation may exist in an area of the image with a gradient. If the difference is large it is likely that the given pixel exists within a gradient, indicating the Niblack result would be the better evaluation criteria for that pixel.

A natural question that arises is what constitutes a large difference for the \(B_n\) selection, as the range of the gray levels varies between images. It was determined through inspection that using twice the standard deviation for the entire image as the difference threshold provided the best results across multiple test cases. While better results can be obtained on any given image by manually selecting a difference threshold, using twice the global standard deviation provided a generalized approach that works well across multiple test cases. Using the global measure of standard deviation also provided better results across test cases than using the local measures of variance and standard deviation calculated from the evaluation windows used in the Niblack method.
Conclusions
Overall, the hybrid approach in the current study provides one more method for the binarization of cellular structure images. The method has shown promise in the binarization of lower resolution, hazy images for the accurate reconstruction of cellular structures of polymer foam materials via micro-focus X-ray computed tomography technology. Experiment results indicate that the accuracy of our approach is remarkably better than that of existing methods in the test cases of polymer foam materials. It leaves open the possibility of future refinement through the inclusion of edge detectors and entropy-based models.

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References
Extended Abstract 7

Title

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Keywords
Case-Based Design, Case Library, Architectural Topology, Semantic Ontology, Visual Language

Introduction
Eastman proposed the building product model (BPM), which is composed of three types of information: semantic, topological and geometric [4]. He also initiated research on the building information model (BIM), which is applied in commercial CAAD tools and is widely adopted by the AEC field [3]. Therefore, architectural design can be regarded as the conversion processing among three types of design information: (1) firstly to declare the “semantic ontology” of design objects such as the semantic features of vacant spaces and physical components; (2) then to develop or search appropriate “topological relations” among design objects to respond to the given problems and design contexts; (3) thirdly to give “geometric prosperities” of every design object to represent the chosen solutions; and (4) finally to validate the required “semantic ontology” based on the chosen “geometric prosperities.”

Architects have the meta-knowledge about how to transfer among three types of design information. But novices need the assistance of design teachers who provide design cases and interpret the conversion processing in order to learn the meta-knowledge. In the past, case library was usually implemented by rational database technology, which required the selection of semantic information of case’s features as the index mechanism. Except for some software and research that have developed tools of spatial topology [10], most of the recent CAAD and BIM research focuses on the geometric properties of physical components for developing parametric design tools. However, necessary “topological information” is usually missing to bridge the semantic information to the geometric properties. Therefore, the meta-knowledge of design information conversion within design cases is usually very difficult to be encoded and retrieved, and BIM tools without architectural topology are not suitable for early design stages.

This paper is a follow-up study to the two previous projects “Smart Topology Retrieval” (STR) [9] and “Smart Spatial Ontology” (SSO) [7]. This paper aims to develop a visual tool entitled “Visual Architectural Topology” (VAT) for the purpose of encoding architectural topologies within design cases of a house case library termed “Open Case Study” (OCS) [8]. By applying previous research results, VAT aims to establish a visual language for representing the topological information of architectural design objects, and also to extend the knowledge representation ability of our design case library.

Main Idea
Knowledge representation in design cases is a major bottleneck in case-based design (CBD) and case-based reasoning (CBR) research. Since design knowledge is usually implicit, especially in the case of ill-defined or unstructured information such as drawings, graphics and pictures, it is difficult to formalize this knowledge into a machine-processable format. As more BIM implementations are used in practical work, BIM may provide an “information-rich” depository of BIM-based case libraries in the future. However, for important precedents outside of practice or before the development of BIM, it is usually difficult to collect detailed information in order to construct BIM files. In contrast, unstructured information concerning design cases, such as the scanned design drawings and images, are nevertheless easily collected and stored in case libraries.

The current method for indexing unstructured information in design cases usually relies on the attachment of semantic tags. The advantages of this method are that it is open, flexible, and easy to implement, but simple semantic tags cannot adequately represent the relationships among topological and geometric information. Therefore, employing the open-annotation strategy of an OCS library, this paper proposes an open and adequately-formalized tool that can assist users to visually represent their interpretations of topological knowledge. Rather than providing a rigid representation framework for unstructured information, the approach is based on (1) the semantic ontology of topology, (2) graphic annotations attached to unstructured information, and (3) visual validation when encoding topology (Fig. 1).
Based on the prior knowledge consisting of the ontological techniques in STR, and predefined topologies of SSO, the VAT project is devoted to developing a visual language tool assisting users to represent the topological knowledge in design cases. VAT improves the topological knowledge representation of the OCS case library from the spatial topologies of house plans to free and open interpretations of other unstructured information in the library. Via the semantic association of ontologies with topologies, VAT can improve on SSO's graphic-based search mechanism, and assists users to retrieve and learn topological design knowledge more efficiently from unstructured information in design cases.

**Conclusions**

Since visual media can more easily represent architectural topologies, it is necessary to develop a visual tool in order to solve the problem of encoding, indexing, and retrieval of architectural topology meta-knowledge within a case library. This tool should provide necessary architectural topology functions, which can bridge the semantic and geometric information of design objects, and assist users in encoding and representing information conversion meta-knowledge among semantic, topological, and geometric forms of information.

The VAT project in this paper illustrates our methods of improving the representation of topological knowledge within the OCS case library. The recognition results of users applying VAT provide a visual language for communication between different agents in the system, including human designers and reasoning machines. VAT not only encompasses more topological knowledge within the design case library than spatial topologies in plan drawings, but also provides a foundation for development of the next generation of design assistance tools, which should be based on the conversion of the three types of design information used in BIM systems.

**Acknowledgements**

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**References**


*International CAD Conference and Exhibition, Final Program CAD’13 Volume 10*
Extended Abstract 8

Title
Parametric Design and Structural Analysis of Deployable Origami Tessellation

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Keywords
Parametric modelling, origami, deployment, LS-DYNA, permutation, scripting, tessellation

Introduction
This paper presents a research study on a geometry and mechanism of origami for generating a deployable tessellation structure that will be tested as a large span structural system. The study is derived from a biomimetic approach related to research on the folding and unfolding mechanism of biological matters such as leaves and insects’ wings. Analog models were initially produced for studying the origamic deployment mechanism followed by a process that translated the model into a scripting based form generation using a parametric system to propagate different permutations of the same origami family. Each permutation was then evaluated for its structural performance in order to optimize the geometry for a given scenario. The workflow requires interoperability between the parametric system (Grasshopper/Rhino), Excel, and structural simulation system (LS-DYNA). The research investigates the possibilities of extracting geometric and mechanical principles of microstructure for its application on a larger scale structure as an architectural element.

A recent paper by the authors discussed the general process from biological inspiration to structural evaluation of the selected origami structure [1]. This paper continues the discussion with more additional information related to geometric principles of the selected origami for the case study and the technical details on the interoperability between the parametric and the structural system.

Main Idea
In the first phase, the research observed analog and digital models representing the folding and unfolding mechanisms of leaves, insect wings, segments of earwigs, grasshoppers, crickets and praying mantes. In the case of insect wings, the research includes the understanding of which creases are produced when the folding and unfolding mechanism occurs at any given angle while paying attention to the tension lines when the folding occurs. In the case of leaves, the research includes the understanding of the level of structural compactness resulting in maximum symmetrical foldings, which depends on the existing variables of the leaf such as angles between the mid-rib and veins.

Fig. 1: diagram of folding mechanism, earwig

In the second phase, analog models based on origami folds were proposed. The making of the analog models involved some basic origami operations such as mountain and valley folds, squash folds, pleats, and reverse folds. The scale of the analog model constructed varied from micro to larger paper folds in order to observe the origami deployment mechanism that resulted from the creases. This phase investigates the kinetic mechanism in each state of deployment of the various scales of the built rigid
origami through the analog model and makes an initial approximation of the level of deformation the origami can tolerate in each state of deployment in order to understand its potential flexibility and stiffness.

Fig. 2: Diagram of folding patterns of leaves (left), analogue models (right)

In the third phase, selected analog models of the origami were translated into a parametric system followed by a structural evaluation (LS-DYNA). This phase dealt with discovering the mathematical principle of the geometry and the mechanism of the origami. The basic principles of rigid origami such as restrictions on the face panel stretchability were embedded in the parametric model, and the principle of the folding and unfolding of origami was implemented in the system by using the trigonometric function for solving the rotation angle of the hinge. The generated model from the parametric system was then transferred to LS-DYNA for structural evaluation, which was bridged via vb.net scripts to produce syntactical interoperability. One difficulty that arose during this process was related to the complexity of the data exchanged during the process. Grasshopper and Rhino operate with independent NURBS surfaces, whereas LS-DYNA operates with polygonal meshes. The details of this interoperability issue will be discussed later in this paper. After successfully exchanging the data and running the simulation, numerical feedback from LS-DYNA for nodal displacements and force reactions of the model were converted to scatter charts in Excel for further analysis on the structural potential of the model. In the last phase, prototypes were developed through digital fabrication, and the model's structural properties were further tested.

In phases 3 and 4, the understanding and selection of materials and manufacturing strategies played a pivotal role during the whole process. In this research, PETG (glycol-modified polyethylene terephthalate) was considered suitable to satisfy the conditions of the kinematic requirements and deployability of the origami structure. PETG material has high tensile strength (53.7 ± 1.9 Mpa), which allows high elongation at yield, and PETG also has high impact resistance, especially at relatively higher temperatures (114 ± 25 J/m at 25.5 °C) [2]. High tensile strength allows PETG to have a higher plastically deformable level without fracturing, which is suitable for its application to the retractable nature of the studied origami structure. In addition, PETG is easy to mold due to its noncrystallizable characteristic, which makes its viscous flow temperature lower than 130°C [3]. Because it is easy to process and mold, PETG makes the entire fabrication process more efficient in general. The usage of PETG material for the case study will be described in more detail later in this paper.

Conclusion

The overall study proved to be successful in terms of understanding the geometric and structural behavior of the Miura-ori through a parametric modelling approach. Interoperability from the parametric to the structural analysis system is achieved in that all data of nodal coordinates as well as element construction to materiality are successfully exchangeable. However, the overall data exchange requires a tedious process and proved to be inefficient. The data filtration of Nodfor and Nodout from LS-Dyna requires a purely mathematical process and proved to be successful in terms of data management but still lacks visual interface.

References


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Extended Abstract 9

Title
Application of Luminance Contrast in Architectural Design

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Keywords
Luminance Contrast, Space Perception, Design Parameter, High Dynamic Range Imagery

Introduction
Enriching the spatial experience of an architectural space within its limited structural boundary is one of the goals in architectural design. The manipulation of physical configurations to create a misinterpretation of the depth cue has been found an effective way to create a false perception of the spatial depth in many architectural examples. Luminance contrast has been identified as effective visual information to create an illusory depth effect on a planar surface [3], and it can cue the relative distance in three-dimensional settings [5]. However, the cause-and-effect relationship between the physical configuration, the luminance contrast, and the resulting spatial experience has not been established yet. In this study, psychophysical experiments were conducted in a perceptual realistic computer environment. The visual realism of the final image in terms of studying the depth perception in relation to the lighting has been established in a previous study [4]. The experiment investigate the relationship between the architectural configuration of skylights, the scene luminance contrast rendered by the daylight that is admitted inside, and the effect on depth perception. Design principles of utilizing luminance contrast through daylighting to enrich the spatial experience of an architectural space were generalized to conclude this study.

Main Idea
The experimental scenes were generated from the architectural configuration illustrated in Fig. 1. The hallway is comprised of four 6 m × 6 m × 4 m modules. The camera is set at a height of 1.6 m and it focuses on the center of the visual target. The visual target is a sphere with a radius of 30 cm, which floats 1.3 m above the ground. The initial position of the visual target is located at a distance of 15 m from the camera. Each module has a 2 m × 2 m skylight in the middle of the top ceiling. The skylight can be open, half closed, or closed to admit different amounts of daylight into the space.

Figure 2 illustrates the test scenes in which the visual target is located 15 m away. The four skylights are controlled in different ways to create three conditions: luminance contrast between the visual target and the foreground is greater than (F > B), equal to (F = B), and lower than (F < B) the background. The rendering parameters such as the surface materials, location, date and time, and options of output quality were all kept constant in the lighting simulation program RADIANCE [6]. The three skylight configurations were simulated under the same CIE sky models, defined by the International Commission on Illumination (Commission Internationale de l’Eclairage), located at latitude 25.1° and longitude 121.6°, with and without a sun patch to create two sets of test scenes.

Fig. 1: The architectural configurations of the experimental scenes.
Fig. 2: Test scenes.

A series of comparison scenes were rendered with the visual target located at varying distances, 12, 13, 14, 15, 16, 17, and 18 m, from the viewpoint under the same CIE sky model, without a sun patch. The skylights were all open to equalize the luminance contrast of the visual target between the foreground and the background. The Method of Constant of Stimuli was
used to measure the perceived distance of the visual target under different lighting conditions [2]. The test scene was presented with a comparison scene simultaneously to a subject. The subject was required to report which target was perceived to be closer. Test scenes of different conditions were presented with 7 different comparison scenes 10 times in a random order. Each subject needed to make a total of 420 perceptual judgments.

The Probit analysis was used to derive the measured perceived distance of the visual targets in different test scenes [1]. Table 1 compares the measured perceived distances of the visual target in the $F > B$ and $F < B$ conditions against the measured perceived distance in the $F = B$ condition, with and without application of the sun patch. The result given in the table demonstrates that when the luminance contrast against the background was lower, the perceived distance increased by 6% and 9.3% for sky conditions with and without the sun patch, respectively. Similarly, the perceived distance decreased by 4% and 2.3% with and without the sun patch, respectively, when the luminance contrast against the background was higher. It is thus concluded that lowering the luminance contrast against the background can effectively increase the perceived distance of the visual target in a space, and the effect is more pronounced when direct sunlight is avoided.

<table>
<thead>
<tr>
<th>Luminance Contrast</th>
<th>$F = B$</th>
<th>$F &gt; B$</th>
<th>$F &lt; B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perceived distance of the visual target 15 m away under the CIE sky model without a sun patch</td>
<td>14.813 ± 0.079 m</td>
<td>16.192 ± 0.065 m</td>
<td>14.469 ± 0.086 m</td>
</tr>
<tr>
<td>% increase</td>
<td>9.3%</td>
<td>-2.3%</td>
<td></td>
</tr>
<tr>
<td>Perceived distance of the visual target 15 m away under the CIE sky model with a sun patch</td>
<td>14.796 ± 0.075 m</td>
<td>15.678 ± 0.078 m</td>
<td>14.195 ± 0.088 m</td>
</tr>
<tr>
<td>% increase</td>
<td>6.0%</td>
<td>-4.0%</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 1: Comparisons of the relative perceived distances.

Conclusions
The light sources that can manipulate the luminance distribution within an architectural scene include daylight and artificial light. Instead of artificial light, the daylight was employed in this study for two reasons: one, as the daylight changes throughout the day, time, and sky conditions, it allows more dynamic scene luminance distribution and the resulting spatial experience; and two, introducing daylight into an architectural space requires a formal and structural configuration that is often determined in the early design process.

The objective of this study is to generalize a set of initial principles to configure the physical configuration to introduce daylight that renders the scene luminance contrast to enrich the spatial experience. Although the architectural configuration examined in this study is limited, the perceptual studies do demonstrate that by manipulating the physical configuration of skylights, one can control the daylight that is admitted inside to create the desired luminance contrast for the composed architectural scene. Because the study used a visual target in a space to measure the effect of the luminance contrast on depth perception, the general principle of utilizing luminance contrast as a design parameter is limited to the setting that has a visual target in a scene. The initial general principle utilizing the luminance contrast and a visual target to enrich the spatial experience of an architectural space can be concluded as below:

- Arrange a visual target to be in the center of a scene to direct the visual attention.
- To increase the depth perception of the visual target in a scene, configure the physical structure to manipulate the luminance contrast between the visual target and its background to be lower than the foreground.
- To ensure the effect, use diffused daylight to avoid a sharp shadow that results from direct sunlight.

References
Extended Abstract 10

Title
Data consistency and conflict avoidance in a multi-user CAx environment

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Keywords
Multi-user CAD, data consistency, collaborative design

Introduction
Traditionally, PLM applications manage data conflicts by restricting file editing access to a single user, using secured file check-out and check-in methods. Multi-user tools will require simultaneous editing access to those same files by a collaborating group, with new requirements for data flow management and data consistency in a distributed user network. We define data consistency as the maintaining of the desired form and intent for the data in the midst of several users working on the same model and possibly the same features within that model. Without an effective method to manage CAx data consistency, multi-user CAx tools become useless as would any software tool that did not maintain the integrity of a user’s data.

Our research develops a data consistency architecture and system to protect data and prevent data conflict in a collaborative CAx environment. First, situations that could compromise data consistency and/or introduce data conflict in a collaborative design session are considered. Next, a methodology and implementation for avoiding and/or preventing these situations are presented. This system includes a user interface and procedure that could be adapted to an existing CAx system through its API. The user-interface and procedure for the system is then created and implemented into the multi-user CAD plugin CATIA Connect, although it could be similarly integrated into several commercial CAx systems.

Main Idea
A collaborative CAx system based on a relational database is particularly vulnerable to update conflicts and delete conflicts. This vulnerability arises as several users are updating and deleting the same data simultaneously in the CAx system. An update conflict occurs when the replication of an update to a row (or data in a database) conflicts with another update to the same row. Update conflicts can happen when two database transactions originating from different sites update the same row at nearly the same time. An update conflict could also occur if one client has several local modifications which have not been propagated to the database (possibly due to an interrupted network connection) then those changes are all propagated at once when the network connection comes back online. If there are any modifications to existing data that happened while the network connection was interrupted, an update conflict could occur. A delete conflict occurs when two transactions originate from different sites, with one transaction deleting a row and another transaction updating or deleting the same row, because in this case the row does not exist to be either updated or deleted [1].

The most realistic approach for data consistency control in multi-user CAx involves locking parts of the entire CAx model to prevent problems with data consistency [2]. Advantages are easy implementation - no special transformations of data are required as data is transferred - and the effective prevention of both update and delete conflicts. The strictest realistic approaches fully lock the collaborative design session allowing only one user to edit the model at a time, and the remaining collaborative users to have a view-only mode of the model. More segmented approaches have been implemented in some of the Microsoft Office 2010 collaborative document editing software, allowing certain segments of the document to be locked for editing, while allowing the rest of the document to be open for editing by other collaborators. Changes to the document are not propagated automatically, rather are broadcast to other users when the document is saved and when the user chooses to broadcast the changes.

Our research considers a new method to preserve data consistency in a multi-user CAx environment. The new method includes three constraint types which work by constraining and controlling both features and user access across an entire multi-user CAx platform [3]. See Fig. 1 for several examples of feature lists, feature coloring constraints, access permissions, and administrative access assignment. The first constraint type includes locking or reserving features to enable only one user at a time to edit a given feature. The second constraint type, collaborative feature constraints, allows flexible constraining of each individual feature in a
model, and the data that defines it. The third constraint type, collaborative user constraints, allows the constraining of user permissions and user actions individually or as a group while providing as much flexibility as possible. Multi-user management of collaborative access is an important research issue. For example, when the All Users option is selected in the administrative form of Fig. 1, the global collaborative constraints menu becomes active for all features. In addition to creating global permissions for each assembly/sub-assembly/part/feature, this will allow the administrator to create or arbitrate any collaborative constraints that need modification. Global permissions for each assembly, sub-assembly, part, and feature will override the user-specific features. The hierarchy of the global constraints could be modified to fit the needs of the specific application. Also, this form could potentially be used to manage task-based constraints or spatial model decomposition as suggested by Marshall [4] if such were also available in the same implementation.

Fig. 1: Interfaces for data consistency locking and access rights

To demonstrate effectiveness of these methods, mock-ups and implementation guidelines are presented. A proof-of-concept implementation was built using CATIA Connect, a multi-user CAD prototype developed as a plugin to Dassault Systemes CATIA V5. Using this implementation use cases are provided to show how this method provides important tools that increase collaborative capabilities of a multi-user CAx system. By using the suggested method design teams will be able to better control how their data is used and edited, maintaining better data consistency and preventing data conflict and data misuse.

Conclusions
We consider an easy to use and understand interface for users in a collaborative, multi-user CAx design environment to eliminate update and delete data conflicts. The three-state selector to reserve/lock/release features will help users collaborate within shared collaborative design space. The visual awareness conveyed by the different coloring of features as they are locked or reserved will serve as an additional avoidance method for data conflicts, as it lets users know where in a CAx model other users are editing, and which features they are allowed to edit. The collaborative feature constraints developed will help protect models as the CAx data is shared with several different users. The administrative interface and collaborative user constraints will help a CAx design team define the roles of individuals on their team and protect their data from being changed inadvertently or by unauthorized individuals when it is shared with others. Overall, this data consistency method allows collaborative CAx software to be used more safely and effectively because it protects the data created by the software, controls how the data is used, who can modify it, and who can access it.

References
Extended Abstract 11

Title
Robust Slicing Procedure based on Surfel-Grid

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Keywords
Rapid Prototyping, geometric modeling, Slicing accuracy, mesh, point model, grid structure

Introduction
The trade-off between accuracy and efficiency is of major concern in rapid prototype, where STL (Stereo Lithography) [1] is the most commonly used format to present a CAD model. Traditional slicing algorithms slice the triangular facets on a STL model to generate the rapid prototyping layer contours. The challenge to achieve the accuracy/efficiency trade-off becomes critical when a STL model contains a large number of triangles.

Previous work done by Zeng et al. [5] (denoted as Zeng’s in the sections below), speeded up the layer decomposition process by adopting a one-dimensional LDNI (Layered Depth-Normal Images) sampling [5], which is independent of the geometry complexity. However, even by adopting high sampling resolution, accuracy of the generated contours is not entirely satisfactory for models with fine features. The objective of this paper focuses on achieving accurate layer contours in a more efficient manner without scarifying the high efficiency.

Main Idea
In this paper, a new 2D grid based slicing algorithm is proposed. The algorithm overview illustrated in Fig. 1.

Fig. 1: Algorithm Overview.

Two dimensional LDNI sampling are adopted in this work. The two in-plane Grid forming orthogonal rays, the sampling points (orange and blue points) and their associated normal vectors, denoted as surfels [4], locating on the edges of Grid are shown in Fig. 1. The accuracy of slicing contours can be improved significantly by preserving sharp features, which can be reconstructed by using the normal vectors of surfels. A Grid with surfels is called a Surfel-Grid (see Fig. 1(c)). In this structure, surfels preserve fine features and the Grid provides neighborhood information for each surfel, which plays an important role in guaranteeing the efficiency and topologically consistency for loop construction in next step.

After Surfel-Grid generation, the mesh model is discretized into layers of Surfel-Grids. Suppose the input mesh model is closed with good connectivity, it should occupy a set of continuously connected Cells for each layer. Therefore, the loop construction upon the Surfel-Grid can be simply decomposed into line-segment connections within each Cell. Benefit from the neighborhood information and cell validity criteria of Surfel-Grid, those line segments can be joined in sequence efficiently. Unlike Marching Cubes [2], this loop construction algorithm is simpler without node status pre-evaluation and pattern identification from look-up table. The resulting slicing model is fully compatible with layered fabrication.

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
To estimate the approximation error and to compare the slicing accuracy with other slicing algorithms, two criteria are used to evaluate the accuracy for the slicing contours: Maximum Chord Error $e_{\text{max}}$ and Chord Area $e_{\text{area}}$, where $e_{\text{max}}$ is the maximum Hausdorff distance between boundary of original model and the slicing contour [3]; and $e_{\text{area}}$ is the enclosed area between the boundary of original model and the slicing contour.

To demonstrate the main characteristic of the proposed algorithm, an example which contains multiple loops with many sharp features as illustrated in Fig. 2 was tested. From the detail view (Fig. 2(c)) of the area circled in Fig. 2(b), the slicing contours (green curves) of the proposed algorithm fits the original mesh model (red) and all of sharp features are preserved properly. In contradiction, the deviation between slicing contour (in blue) and the boundary of original mesh model of Zeng’s work is quite obvious (see Fig. 2(d)).

![Fig. 2: Example model: (a) Original mesh, (b) Slicing model, (c) detail view in (b), (d) detail view of Zeng's work.](image)

In order to more specifically compare the accuracy and efficiency of this and Zeng’s slicing algorithm, the experiment involves comparing approximation errors (i.e., $e_{\text{area}}$ and $e_{\text{max}}$) w.r.t. the total slicing time $T_t$. Since the number of layers may not affect the contour accuracy, the layer thickness was fixed and increasing the sampling resolution, the total slicing time increase with sampling density. The corresponding $e_{\text{area}}$ and $e_{\text{max}}$ of example model in Fig. 2, are plotted according to $T_t$ for both work in Fig. 3.

![Fig. 3: The trends of approximation errors ($e_{\text{area}}$ and $e_{\text{max}}$) with respect to the total slicing time ($T_t$): (a) $e_{\text{area}}$-$T_t$, (b) $e_{\text{max}}$-$T_t$.](image)

**Conclusions**

Both $e_{\text{area}}$-$T_t$ and $e_{\text{max}}$-$T_t$ show a similar trend in this and Zeng’s work - slicing accuracy is improving while slicing time becomes longer. However, this work presents an improved accuracy overall, since both the $e_{\text{area}}$-$T_t$ and the $e_{\text{max}}$-$T_t$ show better results. Moreover, this work takes 15% to 50% less time than Zeng’s work to achieve the same accuracy, which means higher accuracy and better efficiency.

**References**


Extended Abstract 12

Title:
Quasi-Log-Aesthetic Curves in Polynomial Bézier Form

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Keywords
log-aesthetic curves, polynomial Bézier curves, logarithmic curvature graphs

Introduction
Planar log-aesthetic curves[1,2,3,5] are curves with monotonically varying curvature and linear logarithmic curvature graphs. Previous methods for approximating planar log-aesthetic curves include quasi-log-aesthetic curves in rational cubic Bézier form[6] and placing Bézier control points on a discretized log-aesthetic curve[4]. In quasi-log-aesthetic curves in rational cubic Bézier form, we have to use rational curves instead of polynomial curves. In the method of placing control points on a discretized log-aesthetic curve, the degree of Bézier curves needs to be very high to maintain the linearity of logarithmic curvature graphs. This paper presents a method for approximating planar log-aesthetic curve segments by polynomial Bézier curves using Taylor series of log-aesthetic curves. We compare the proposed method with the previous methods. We also propose a method for $G^2$ Hermite interpolation.

Main Contributions

1. Quasi-log-aesthetic curves in polynomial Bézier form

We propose quasi-log-aesthetic curves in polynomial Bézier form which approximates log-aesthetic curves. Let $\alpha, \Lambda, \theta$ be the slope of the logarithmic curvature graph(LCG), the parameter for scaling (if $\alpha \neq 1$) or changing the shape (if $\alpha = 1$) of the curve, and tangential angle. See [5] for the details of $\Lambda$. The equation of log-aesthetic curves in terms of tangential angle on the complex plane is

$$
F(\theta) = \begin{cases} 
\int_0^\theta e^{i(\alpha + i)\phi} d\phi & \text{if } \alpha = 1 \\
\int_0^\theta ((\alpha - 1)\Lambda \theta + 1)^{\frac{1}{\alpha - 1}} e^{i\phi} d\phi & \text{otherwise}
\end{cases}
$$

(1)

where $i$ is the complex unit. We expand Eqn.(1) as a power series of $\theta$ at $\theta = c$. We use $c = 0$ (if $\alpha < 1$) or $c = 1$ (if $\alpha \geq 1$) since we found that it produces good approximation. By replacing $\theta$ by $t$ and truncating the terms whose degree is higher than a user-specified value $n$, we obtain a power basis function of degree $n$. Changing the basis to Bernstein basis, we get a Bézier curve segment whose tangential angle changes from 0 to 1. Then we apply the de Casteljau algorithm to compute the control points so that the change of tangential angle becomes a given value. The generated curve segment is a quasi-log-aesthetic curve segment in polynomial Bézier form.

2. $G^2$ Hermite Interpolation

We propose a $G^2$ Hermite interpolation method of quasi-log-aesthetic curves in polynomial Bézier form. Since the quasi-log-aesthetic curve is an approximation, the parameter $t$ is not exactly corresponds to the tangential angle. Thus we cannot directly apply the $G^2$ Hermite interpolation method described in [5]. By adding the process of adjusting the parameter $t$ so that the change of tangential angle becomes the given value to the method in [5], we show that we can generate a quasi-log-aesthetic curve segment in polynomial Bézier form.

Results

Fig. 1 compares the proposed method with Miura’s method[4] which discretizes the equations of log-aesthetic curves by a constant tangential angle or a constant arc length. In Fig. 1 (a) to (f), the degree of the curve is 6, 10 and 20 from left to right. In all the method, the approximated Bézier curve shown in blue gets closer to the log-aesthetic curves shown in red. Our method produces better curve segments and the linearity of the LCG is better than Miura’s method. Fig. 2 shows some examples of International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
interactively generating the curve segments with their curvature plots and LCGs. The curve segments can be generated in real time.

![Curvature plots and LCGs](image)

**Fig. 1** The generated curve of $\alpha = \log(l(a), (b), (c))$ and $\alpha = \log(l(d), (e), (f))$ and their LCGs. In (a) to (f), the degree of the curve is 6, 10 and 20 from left to right.

![Interactively generated curve segments](image)

**Fig. 2** Interactively generated curve segments, its curvature plot and LCGs.

**Conclusions**

We proposed quasi-log-aesthetic curves in polynomial Bézier form and showed that it is a better approximation than the method shown in [4]. We also proposed a $G^1$ Hermite interpolation method for a quasi-log-aesthetic curve segment by specifying two endpoints and their tangents. In comparison with quasi-log-aesthetic curves in rational cubic Bézier form [6], the proposed method can generate polynomial Bézier curves. If a quasi-log-aesthetic curve segment in polynomial Bézier form gets closer to a circular arc, its approximation gets worse due to the limitation of polynomial curves. However, log-aesthetic curves are especially meaningful when they are not close to circular arcs, so the proposed quasi-log-aesthetic curves are useful.

**References**

Extended Abstract 13

Title
A knowledge-guided approach to line-curve intersection

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Keywords
Intersection, robustness, tolerancing, knowledge-guided systems, NURBS

Introduction
Intersection algorithms have been the subjects of intensive research since the early days of modern CAD/CAM. The majority of intersection methods published in the literature deals with parametric entities, subdivision techniques, algebraic methods, special entity types such as natural quadrics, evolutionary algorithms, or computational geometry techniques. A few honorable attempts at robustness revolve around those of solid modeling or the use of interval arithmetic. The line segment has played an important role in engineering design; it is used for two dimensional design, trimming off excess parts of curves meeting with straight edges, cutting parts of 2D drawings (potentially meeting with anomalies), performing inside/outside tests using ray shooting, processing 2D objects via scan-line methods, etc. Another important application is in nuclear engineering where the flying path of a neutron needs to be intersected with curves fast and efficiently (after the accident in Fukushima, nuclear engineers are looking at non-standard geometries represented by NURBS). Although general curve-curve intersection methods could handle lines, our experience shows that special purpose methods are by far more reliable and accurate.

It is our belief that the issue of robustness requires a whole lot more than just mathematics. The lack of robustness comes from many sources:

- **Geometric uncertainties**: mostly the result of lack of knowledge about the entities, i.e. we are not certain what the intersections are due to not seeing and understanding the type of the curve and the relationships between the entities.
- **Geometric anomalies**: cases like cusps, tangent points, overlapping entities, degenerate cases can make the numerical code fail.
- **Tolerance inconsistencies**: during the course of the algorithm a myriad of tolerances, e.g. manufacturing, parallel, perpendicular, angular, algebraic, etc, are used that may have no relationship to one another, e.g. how to adjust a tolerance used in an algebraic equation to ensure the results are accurate to a model space manufacturing tolerance.
- **Numerical/imprecise computation**: round-off errors that propagate through the system and cause inaccurate results, non-convergence, singularity, etc, create a chaos in most numerical code used in CAD/CAM systems.
- **Inappropriate mathematics**: although math is nice and well in itself, the implementation of different techniques or formulae produces spectacularly different results from the point of view of accuracy, speed and reliability.
- **Inappropriate error bounds/measures**: almost all numerical techniques require some kind of error estimates or bounds on the error. There remain a few challenging problems such as parametric vs. geometric errors or computing tight error bounds to avoid data explosion.
- **General or special purpose algorithms**: general purpose methods can be applied to many problems, they are easy to write, however, maintenance can be a nightmare as they tend to fail frequently and can be quite slow. On the other hand special purpose algorithms work only on specific problems, e.g. cylinder-cylinder intersection, they are tedious to write, however, they are fast, robust and easy to maintain.

The algorithm presented in this paper satisfies the following robustness requirements:

- **Consistent tolerancing**: it uses only one tolerance, a model space point coincidence tolerance. No other tolerances are allowed.
- **Global solution**: it finds all intersections regardless of anomalies or geometric complexity.
- **Accuracy**: the intersections are found to within engineering tolerances (we use 10^-6 throughout the algorithm).
- **Performance**: the algorithm is robust and computes all intersections in real time.
• **Bounded geometry:** curve and line segments are intersected, i.e. the intersections are properly clipped or avoided if they fall outside the arc.

• **Commercially verified:** the algorithm is implemented with KGNurbs, a derivative of a commercial NURBS kernel created by the second author.

• **Data exchange:** the intersections can be reproduced at the receiving end as KGNurbs builds a knowledge base that allows design replay.

Our decades of experience in geometric computing has taught us a lesson: the more we know about the entities we compute with, the better the robustness of our algorithms. During the days of engineering drawings where intersections were computed by hand, everything seemed more reliable: the engineer could see the entities, knew where they were and what the intersections must be, and had the experience to construct the intersection points or the curves. Intersection algorithms tend to be blind: they are searching for something they know nothing about. Our biologically inspired knowledge-guided system relies on a knowledge base (basic knowledge about the entities combined with a sophisticated relationship graph) and knowing what the entities are and how they are related, e.g. seeing their relative positions. Our experience has demonstrated that special purpose intersection algorithms are far superior to general ones enhancing the robustness immensely.

**Methodology**

The algorithm presented herein has the following major components:

1. Find information about the entity types such as lines (defined as linear splines) or circles (one can also consider other types of conic sections). The line-line case is robust, however, the line-circle case is non-trivial due mainly to the need to recover the parameter and that circles are defined differently in different systems, e.g. degree 2 versus degree 5, producing different parametrizations.

2. Decompose the NURBS curve if it has a straight-line path. Based on the convex hull property, if degree plus one or more control points are collinear, the curve has a line path. Note that the curve is not a line on that path, it is still a high degree curve exhibiting collinearity on a segment. Extracting these segments is important because of the numerical issues arising from line-curve overlap.

3. Get a biarc approximation of the curve even if it is a line segment. Note that our biarc curves approximate both the geometry as well as the parametrization, which is necessary to recover both the geometric as well as the parametric locations of the intersection points.

4. For each biarc, get the intersection points on the line segment and the biarc (Bezier circular arc) and recover the local (Bezier arc) as well as the global parameters.

5. Use the line-biarc intersection points and their parameters as start points for a Newton-type method to home in on the true intersection points. Note that the biarc approximation tolerance can be much larger than the required intersection tolerance as we are looking for good start points (in our system we used $10^{-3}$ as a biarc tolerance and $10^{-6}$ for intersection tolerance).

6. Purge the intersection points and generate the output. Using the biarc approach multiple intersections are possible at the locations where the biarcs meet. However, these can be identified and purged out.

7. Update the knowledge base with the newly created relationships saving all the parameters necessary to reproduce the results.

**Summary**

A robust algorithm to compute all the intersections between a line and a NURBS curve is presented. Instead of making the problem as part of a general purpose curve-curve intersection problem, we argue that general purpose intersection algorithms are inferior to special ones when the emphasis is on robustness, accuracy, speed and reliability. We believe that robustness can be achieved in CAD systems without changing the arithmetic. It requires knowledge, careful algorithm design and consistent tolerancing.
Extended Abstract 14

Title
Re-engineering of the haptic feedback of a dishwasher door

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Keywords
Virtual Prototyping, Haptic Interaction, Reverse Engineering, User Experience

Introduction
By observing potential buyers of consumer products at the selling point it can be easily noticed that they enjoy interacting with the product and its variants they are interested in. The aim of this exploratory phase is to build a personal perception of the product quality. That perceived quality could be seen as the result of a multi-criteria analysis, which involves the brand, the user expectations in terms of product functionalities/cost, and the user experience.

The user experience is created on the basis of the multisensory interaction with the product, which involves all the senses, even those buyers are not aware of [1]. This is a well known issue for companies operating in the automotive field that have spent a lot of efforts in years in trying to optimize the sound of closing doors [2], and recently also their haptic feedback [3]. Recently, also companies in the field of household appliances are getting interested in the problem [4,5]. Anyway, despite this growing interest there is still a lack in terms of methodological approaches to face this problem.

When designing the user experience of new products, companies usually perform comparative tests involving potential customers as well as marketing experts, and taking as samples their own products or the so-called “best in class” products of competitors. The outcome of these comparative tests is the expected behavior of the new product that is a sort of mix of the most appealing features of the tested products. Once the optimum behavior is captured, the role of the marketing experts is to translate it into project targets, and then into design specifications with the help of R&D engineers. However, a methodological approach that takes into account all these steps is missing. Indeed, the resulting design specifications are mainly qualitative indications. Besides, the initial phase of testing is limited, being based only on products already available on the market. The risk of such an approach is the homogenization of new products rather than their differentiations.

The aim of the research described in the paper is to fill the gap between marketing people who identify a desired behavior of the product and engineers who must make it feasible. The approach has been tested on a case study provided by Indesit Company, an Italian manufacturer operating in the field of the household appliances. Specifically, the proposed approach has been focused on the re-engineering of the force feedback of a dishwasher door.

Main Idea
Figure 1 schematically represents the main steps of the methodological approach we have defined. This goes from the analysis of an existing product, to the creation of its virtual prototype, and then it moves towards the tuning of the user experience for the definition of the new design specifications.

Fig. 1: The main steps of the methodological approach: from the analysis of an existing product to the design of a new one.

The consumer product used as case study is a freestanding dishwasher. The objective of the analysis was to re-engineer the force feedback exerted on the user’s hand while opening and closing the door. The company provided the geometrical CAD model
of the dishwasher. The forces returned by the interaction with the door have been acquired by means of some sensors: a load cell, an inclinometer (as in Figure 2-a) and a gyroscope have been used. Finally sounds have been recorded by means of a microphone.

Subsequently, it has been created a multisensory simulation of the product in the virtual environment, including pieces of information for the three senses (touch, hearing and sight). The values of the force, angle and angular velocity previously acquired have been used to tune the mathematical model that describes the haptic rendering in the interactive virtual prototype (represented in Figure 2-b). This has been obtained by means of some optimization algorithms. The full mechanical model has been described using the commercial software LMS- Amesim (www.lmsintl.com/).

The mathematical model that represents the haptic feedback of the existing dishwasher door has been parameterized in order to represent a more generic door and to be tuned according to user’s preferences. In fact, a potential customer can try the haptic feedback of the original product and ask for some modifications, which can be implemented on the fly thanks to the parametric model of the haptic feedback, until the optimum behavior for him has been obtained. The chosen configuration can be recorded and subsequently used as input for the optimization of a more complex and complete representation of the mechanical behavior of the dishwasher door. The result of the product optimization phase is the translation of the optimum behavior into quantitative design specifications, which can be used as input or targets for the re-engineering of the door behavior.

By means of this methodology the gap between the marketing experts and engineers, which is typical in companies, can be filled since they all can use appropriate flexible models of the product: the marketing experts use the interactive virtual prototype, and the engineers use the mechanical -or other domain- behavior models. The advantage of this approach is that the models are fully integrated.

![Image](image-url)

**(a)** The analysis of the force exerted on the real product; **(b)** The interactive virtual prototype used for tuning the user experience.

**Conclusions**

The methodological approach described in this paper has been validated on a commercially available dishwasher, and the haptic feedback of the door has been re-engineered. Actually the same methodology can be used for the design of new products, by simply removing the first step represented in Figure 1, which is the analysis of existing products. The paper describes in detail all the steps necessary to implement the methodology, by underlining the limitations and the open issues.

**References**


Extended Abstract 15

Title
Negative knowledge and a novel approach to support MCAD education

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Keywords
CAD Education, Design Intent, Feature-Based Design, Knowledge Engineering

Introduction
An essential part of today’s engineering student qualifications, in addition to domain knowledge and problem-solving abilities, is comprised of knowledge and skills related to the use of computer-aided design (CAD) systems in modeling, documentation and communication of product and service designs within global digital engineering environments. Various computer-aided engineering (CAE) tools and product life-cycle management (PLM) systems are about to become as ubiquitous as the CAD systems and tools themselves. In the past decade, for mechanical engineering, feature-based parametric CAD systems have become the de facto standard in professional environments, due to their potential to greatly enhance the efficiency of human-driven design and development processes. However, to translate their potential into actual benefits within a professional environment, the creation of models that can easily be understood and altered by domain experts is an essential precondition (see also discussions in [2, 6]).

As in many other engineering disciplines, in the education of CAD for mechanical engineering (MCAD), traditional curricula were mainly concerned with the dissemination and development of procedural knowledge and skills in the form of know-how related to the operation of CAD systems. Unfortunately, such an educational philosophy does not provide sufficient strategic knowledge and understanding to enable students to use CAD systems as knowledge-intensive design and communication tools to properly develop and convey design intent. This is an inauspicious situation, which is reflected in academia by insufficient MCAD education programs and in industrial settings by a vast number of CAD models that are difficult to understand and difficult to alter efficiently.

Main Ideas
This outline of the main ideas, basic approach and results of research is part of a larger ongoing study into the development and use of a novel framework on negative knowledge aimed at supporting advances in collegiate curriculum design for MCAD education. The empirical part of the study is related to the performance and assessment of graduate students during their laboratory work and exercises within previous and current course work on CAD and feature-based design. Further parts of the study are dedicated to the development of structure analysis for CAD model parts. This is carried out from the newly developed perspective of negative knowledge as a means of action constraint in particular situations and computerized tool development to enhance learning outcomes related to creative problem solving and spatial abilities, with a focus on the capture and communication of design intent.

Problem-based learning strategies, included in and executed during laboratory work and exercises, are now widely recognized as an essential part of today’s advanced science and engineering education. Here, the development of domain knowledge and skills can be approached from two sides, namely the forming of both positive and negative expertise. Such knowledge and skills are related not only to the operation of CAD systems, i.e. basic geometric modeling, but more importantly to cognitive and methodological aspects that are essential for a good design strategy resulting in well-structured, easy-to-understand and easy-to-alter CAD models. While positive expertise is commonly used in education and is also the subject of research in various disciplines, negative expertise is overlooked and ignored in almost all disciplines and areas of academic study, even those considered most important and influential for higher education. Except for some early work on negative expertise in artificial intelligence [3], unfortunately not developed further, research into negative knowledge has been carried out only recently within a very few studies in knowledge management and learning-related research [1, 5]. This circumstance is somewhat surprising considering the fact that an essential feature of professional engineering expertise comprises of knowing what not to do in certain situations in order to avoid serious mistakes and approaches that are inefficient. This essential feature is attributed to knowledge referred to as negative knowledge.

Negative knowledge and expertise are usually acquired within a professional environment through negative learning experiences either as a group or as an individual as a result of making mistakes and reflecting on them in a manner of
retrospective cognition. This is a process that is, in its nature, opposite to its counterpart in education, where positive learning experiences with predetermined objectives and fixed learning goals are prevalent. Now, let us take into account the importance and value that negative expertise carries within a professional environment on the one hand and the shortcomings in engineering education together with the job market driven demand for advanced abilities and skills on the other hand. From these circumstances, we can readily determine that the development of negative expertise as an integral part of CAD education bears significant potential for current and future student generations. Current curricula, and thus projected learning outcomes, have the potential to be improved considerably. Differences in the nature of knowledge transmission and skill development within professional environments and in collegiate learning environments need to be considered. First of all, an approach and framework for the teaching of negative knowledge is required. This needs to be related to the educational philosophy and pedagogy of MCAD education, but not based on retrospective cognition, error culture, and negative learning experiences per se. In the following concepts, the required relationships and the newly developed approach and framework for negative knowledge are outlined.

In both engineering science and applied engineering, each system, service, process and product developed can be described by properties known from concepts relating to domain knowledge and experience involved in its design. Now, if we relate our engineering model and context to a concrete set of attribute values associated with well-known concepts sufficiently describing state and properties at any point in time, we shall soon realize that not every constellation, i.e. model configuration, is desirable for our purpose. For example, we might find that model configurations within a computer-based digital model created during several computer-aided design sessions feature undesirable properties, such as extreme attribute values leading to a possible failure in the function of the design. Alternatively, we might discover that certain configurations violate regulations and/or requirements. These are surely situations that are undesirable, and had thus better be avoided. From a theoretical point of view, desirable situations, indicated by what is considered a good model configuration within a given context employing normative knowledge, represent a reduced set of all possible situations (desirable/undesirable). Here the nature of similarity of desirable situations is determined by reducing variety, which in turn is realized by avoiding undesirable situations by means of restricting actions that have a high tendency (according to what we know and believe to be true) to lead to them. Hence, negative knowledge in terms of knowing what not to do in a certain situation can be conceptualized as a form of action constraint. It limits the variety of situations, and consequently their number, by preventing actions that might result in constellations (model configurations) considered not good, i.e. situations deemed undesirable.

Of particular interest here are significant model configurations, which describe a model configuration in a certain context that is significant in respect to action constraints which in turn are associated with individual actions. These significant model configurations can be related through a mapping to concrete constraints limiting the actions possible in a particular situation. Such constraints will also prevent transitions that alter properties. In addition, they will attribute values defining a good model to certain properties, and they will attribute other values defining a model as not being good to certain other properties. In this framework, action constraints consist of sub-structures that may be either implicit or explicit in nature. These constraints provide a concept that takes into account the portion of negative knowledge, which relates to action constraints spanning various different types of situations. Within this framework, a model is assumed to be the set of engineering models, such as the geometric model, the feature model, and the feature-based parametric CAD model, considered when building associations between model properties, concrete attribute values and significant model configurations. The context is assumed to be a multi-dimensional structure capturing context-related aspects known to be relevant from the domain knowledge, the field of application, the engineering task, etc.

In order to employ this novel approach to negative knowledge for the development of negative expertise, significant model configurations, and means of describing them and relating them to action constraints, need to be determined, using, for example, attribute correspondence relationships [4]. For this step, the first part of an empirical study has been used to provide the actual data and concrete context. The empirical study mentioned consists of the provision and analysis of session protocols and parametric feature-based CAD models obtained during laboratory work and exercises conducted during course work. Analysis results were fed back into the framework to compile actual descriptions relating to central concepts of the framework such as significant model configurations and action constraints. In the case of the latter, considering CAD model creation to be comprised of strategic knowledge that contains methods of good design and declarative/procedural knowledge relating more to geometric modeling and system operation, action constraints were structured in a way consistent to this view of design and modeling.

Conclusions
The results of the empirical work provided sufficient data and insight into mistakes and shortcomings typical of inexperienced MCAD system users and commonly reflected in the design approach, modeling history, attribute configuration, and structure of CAD models. In a second step, those data and insights were related to the novel framework developed, in order to facilitate analysis of CAD model parts, which is being used to determine and formulate domain specific aspects of negative knowledge.
Results of this second step are being used for the development of computerized tools for teaching/learning support and curriculum re-design recommendations currently underway. Implementation of both tools and recommendations is planned for the next academic term.

References
Extended Abstract 16

Title
Designing Log-aesthetic Splines with $G_2$ continuity

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Keywords
log-aesthetic spline, $G_2$ Hermite interpolation, triple log-aesthetic curves, S-shaped curve

Introduction
Recent advancement on Log Aesthetic (LA) curve has been promising and it is now maturing for industrial and graphical design practices. Another independent research indicated that LA curve is the most promising curve for aesthetic design [6]. Recent researches on the LA curve include the implementation of variational principles in order to define the log-aesthetic surface and obtain minimized functionals for free-form surfaces design [8]. In 2009, Gobithaasan and Miura [1] formulated the generalized log-aesthetic curve (GLAC) in a standard form and the slope of the logarithmic curvature graph (LCG) as a function of the arc length of a curve. They also reported that the slope of the LCG of generalized Cornu spiral [4] is given by a linear function [2]. In 2012, Ziatdnov et al. [9] found that some LA curves can be expressed by incomplete Gamma functions analytically and the timestamp to generate them was shortened to 10 times.

In this paper, we propose a method using LA curves for solving a problem to generate a curve for given end points, tangent vectors and curvatures, viz., the $G_2^3$ Hermite interpolation problem. The $G^2$ Hermite interpolation problem was solved, but the $G_2$ Hermite interpolation problem has not been solved up to date. On the other hand, Lan et al. [5] extended Makino’s technique [7] and proposed a new method to solve the $G_2^3$ interpolation problem for the clothoid curve. Since the degree of freedom of a clothoid is insufficient, they used triple clothoids to obtain the necessary degree of freedoms. To note, clothoid curves are a subset for LA curves where the slope of LCG (denoted as $\alpha$) is equal to -1. The DOF of the clothoid and LA curve is the same if we fix the $\alpha$ value. Hence, we extend Lan et al.’s method for the LA curve and solve the $G^2_2$ Hermite interpolation problem using the triple LA curve.

Main Idea
Harada [10] reported that $\alpha$ is closely related to impressions of the LA curve. Hence, it is a common practice to fix the value of $\alpha$ to design aesthetic shapes LA curves. We use triple LA curves as a LA spline for the $G_2$ Hermite interpolation problem. In this paper, a triple LA curve consists of three LA curves which are joined with $G_2$ continuity. For algebraic simplification we assume that the curve is planar, the curvature of the curve is positive or zero and $\alpha \neq 0, 1$. Let the curvature of LA curve is stated as follows:

$$\kappa(S) = \begin{cases} 
  c_{10}S + c_{11} & 0 \leq S \leq S_1 \\
  c_{11}S + c_{11} & S_1 \leq S \leq S_2 \\
  c_{11}S + c_{11} & S_2 \leq S \leq 1 
\end{cases}$$

where $S$ is the normalized arc length defined from 0 to 1 and $c_{ij}$ are constants where $(i=0,1,2)$ and $(j=0,1)$. $S_1$ and $S_2$ can be substituted with any values. However, we basically use $S_1 = 0.25$ and $S_1 = 0.75$ as adopted by Lan et al. [5]. When $\{c_{10}, c_{20}, c_{30}\} \neq 0$, the directional $\phi(S)$ can be written as follows:

$$\phi(S) = \begin{cases} 
  \frac{\alpha}{(\alpha - 1)c_{10}}(c_{10}S + c_{11})^{\frac{\alpha-1}{\alpha}} + c_{12} & 0 \leq S \leq S_1 \\
  \frac{\alpha}{(\alpha - 1)c_{20}}(c_{20}S + c_{21})^{\frac{\alpha-1}{\alpha}} + c_{22} & S_1 \leq S \leq S_2 \\
  \frac{\alpha}{(\alpha - 1)c_{30}}(c_{30}S + c_{31})^{\frac{\alpha-1}{\alpha}} + c_{32} & S_2 \leq S \leq 1 
\end{cases}$$

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
The conditions for satisfying the imposed constraints at end points and $G^2$ continuity at the triple LA curves joints are given by:

$$\kappa, h = \left( c_{i1} \right)^{\frac{1}{a}}, \quad \kappa, h = \left( c_{i0} + c_{i3} \right)^{\frac{1}{a}}$$

$$\phi = \frac{\alpha}{\left( \alpha - 1 \right)c_{i0}} - \frac{a}{\alpha} c_{i1} + c_{i2}, \quad \phi = \frac{\alpha}{\left( \alpha - 1 \right)c_{i0}} - \frac{a}{\alpha} \left( c_{i0} + c_{i3} \right) + c_{i2}$$

We can determine the constants $c_{ij}(i = 0,1,2; j = 0,1)$ using the above conditions as well as the positions of the start and end points. The methodological details will be detailed in the final paper. Figure 1 shows several $G^2$ interpolation examples using the LA curve. The triple LA curves are drawn in red and the length of the blue lines indicates curvature of a point on the curve. These curves show $G^2$ continuity at their joints. Figure 2 shows $G^2$ continuity between triple LA curves with different $\alpha$ values. The advantage of this method is that it can connect two triple LA curves with different $\alpha$'s and at the same time preserving $G^2$ continuity. Figure 3 shows a practical example dealing with CAD data. The original curve used at the upper part of the front window is $G_1$, but we exchanged it with a triple LA curve with $G^2$ continuity.

![Fig. 1: Triple LA curves.](image1). ![Fig. 2: A $G^2$ connection of two triple LA curves.](image2). ![Fig. 3: Replacement by a triple LA curve for $G^2$.](image3).

**Conclusions**

In this paper, we propose a new method to solve $G^2$ Hermite interpolation problem for LA curves as well as a method to generate an S-shaped curve for $G^3$ Hermite interpolation. The details of our method will be explained in the final paper and we will also explain about the treatment of the LA space spiral for $G^2$ continuity. The methods proposed in the paper have been successfully implemented as a plug-in module for a commercial CAD system and is found to be essential for practical design.

**References**


Extended Abstract 17

Title
Direct Slicing of surface models in CAD systems for rapid manufacturing applications

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Keywords
Additive Manufacturing, Rapid Prototyping, Direct Slicing, STL, Siemens NX, Laser Beam Melting

Introduction
Since 3D Systems developed the STL (Surface Tessellation Language) data format in 1987 it has come to be today’s de facto standard for the data exchange and geometry representation in Additive Manufacturing (AM) processes. Even though the requirements for AM interface formats are rising constantly, there is no significant improvement of the STL data format [3]. Also the algorithms for the conversation of CAD data into STL files still do not deliver consistently high quality. Dependent on the used CAD system, conversion errors and syntactic representation errors such as gaps, overlapping triangles and incorrect orientation of normal vectors habitually occur [3], [9].

The disadvantages of the STL format have led to several approaches for improvements. WU and CHEUNG e.g. presented an enhanced STL format which is able to store additional information while accuracy is increased [10]. In 2012, the ASTM has specified the AMF format (Additive Manufacturing File Format). This XML based format is an open standard for AM and is feasible for the storage of additional information like colours, materials and constellations [1]. However, these improved formats still have to convert the native CAD data before they can be processed. Subsequently these files are sliced. This complex procedure of data preparation is accepted and today’s working solution for most rapid prototyping applications. But as soon as it comes to highly specialised products with freeform surfaces these file formats are limiting the geometrical design of AM parts. STL files always need so called “waterproof” volume models. Surface models cannot be processed.

Main Idea
To overcome today’s restraints with regard to the data preparation [4] an approach for the direct slicing (DS) of CAD surface models for Siemens NX is developed here. The DS technique is able to process the native CAD data (e.g. [2], [4-5],[8]) or neutral formats like STEP or IGES ([7]) which represent the original geometry. Since direct slicing offers a lot of opportunities without the tessellation of the 3D geometry, several DS procedures have been examined [6].

In this paper the main reason for the DS approach is the limitation of the existing data preparation and with it the limitation of the desired scan strategy of the laser. The desired geometry for filter elements or turbo machinery parts cannot be tessellated for STL export when the geometry is represented as surfaces. However, increasing accuracy and part quality are moreover good reasons for these investigations. Nevertheless, one chosen geometry is manufactured conventionally by assembling several STL files and via the investigated DS approach (cf. Figure 1) which is explained below.

The main goal of the CAD based DS approach is a Graphical User Interface (GUI) supported CAD application that transfers the requested AM functionalities to the CAD user. The Application is integrated in the CAD System Siemens NX by the use of provided API functions. After defining the build direction by the user, the DS procedure generates directly the slice data as CLI file. Additional file formats are examined. However, CLI files are proved as stable for subsequent laser beam melting pre-process steps.

With DS the geometry is sliced in the CAD system and the necessary polygons are only generated into each layer. In this step, the amount of necessary points in each layer can also be reduced because straight lines only require one start and endpoint instead of mid-line points at the STL-file. Hence, the amount of points in one layer is reduced and can be used for more accurate polygons of curved segments. However, the definition or the part orientation has to be done in the CAD environment by the CAD user first. At present this important step is usually applied during work preparation by the machine operator. Therefore, this knowledge must be provided to the CAD user. Knowledge Based Engineering (KBE) strategies deliver solutions for this problem. State of the art pre-process software delivers good results for AM based on STL files. Useful functionalities of these products must be integrated in CAD system when the DS approach should be accepted by the user. Feature-based support generation in the CAD environment is another possible extension.
Assembly consisting eight STL files (96 faces eight volumes)

CAD part (16 faces, no volume)

Layer with 64 endpoints and 64 line segments

Double exposure of internal walls as result

Layer with 16 endpoints and 16 line segments

Internal walls are exposed once

Fig. 1: STL based and DS approach.

Conclusions
Summarized there is a number of advantages of the DS approach which can be identified. The main reason for this approach is that the STL format is not able to export surface models. Especially for this reason this way for the direct export of slice data as CLI files was developed for Siemens NX. First examinations of this approach were very successful for different laser beam melting parts. Beside this main reason for the DS approach, additional advantages can be identified. With DS, the amount of generated process files is reduced for STL files are not required. This reduction simplifies the state of the art PDM/PLM process because less files and versions have to be handled. In addition, part quality can be enhanced. Furthermore, the native CAD geometry need not be tessellated before slicing and even adaptive slicing can be considered and implemented in this approach prospectively.

References
Extended Abstract 18

Title
Sampling Strategies for 3D Partial Shape Matching and Retrieval Using Bag-of-Words Model

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Keywords
3D Partial Shape Retrieval, Dense Sampling, Pyramid Sampling

Introduction
3D object retrieval has received increasing attention during the past two decades. While algorithms for 3D complete shape matching and retrieval have been intensively investigated, 3D partial model matching are far less explored and well defined. Among various categories of algorithms, visual similarity based methods have achieved state-of-art results [1-4] for complete and rigid 3D model retrieval. In this work, we investigate in depth how the features are sampled has more influence on the representativeness and distinctiveness, thus for improving retrieval accuracy of 3D models. We compare the grid and pyramid sampling of SIFT features to the original salient sampling using bag-of-words model for 3D model representation. Experiments are conducted with varying sampling strategies to obtain the optimal sampling strategies for retrieval efficiently. Results are demonstrated on a public 3D partial dataset in order to generalize this approach.

The contribution of this paper can be summarized in two-folds. First, by identifying the optimal sampling strategies for SIFT feature extraction, we find that it does not necessarily result in higher retrieval accuracy with more features extracted for each model. Rather, the generation of number of views and extraction of local salient features should be more informative and less redundant. Second, we succeed to generalize the proposed methods to SHREC 09 parts query models which no previous methods have been tested on and achieve appealing retrieval accuracy.

Methods
Both query and target models are firstly pose-normalized and then a set of depth-buffer images (resolution 256*256) are generated. From the depth-buffer images, the proposed sampling strategies are applied to extract the local salient features. These features are then vector quantized into a visual dictionary using k-means clustering, and finally each model is represented as a histogram indicating the occurrence frequency of each visual feature from the model according to the dictionary. The similarity of two models is then compared based on the histogram distance.

![Fig. 1: Feature extraction geometry: (a) Dense sampling, (b) Pyramid sampling across multiple scales.](image)

In this work, dense sampling and pyramid sampling are proposed to sample features using the same 128-dimensional vector for description as SIFT, except that the bin size of features and sampling steps are configured, not automatically determined by the original sampling, to find the optimal representativeness of shape. The geometry of dense sampling is shown in Fig. 1(a). The 4 x 4 array window slides from left to right, top to down until covers the whole image domain. The bin size and sampling step determine the scale and sampling frequency of features. There is a trade-off between the representativeness and distinctiveness of the sliding window. Larger window contains more information therefore are more informative, but less distinctive at the same time. So these two parameters must be properly chosen in accordance with the application requirements. On top of the dense sampling, pyramid sampling is to extract features at the same grid as dense sampling but across multiple scales. The multiple-scale feature frames are shown in Fig. 1(b).
Experiments and Results

In this work, we use the same datasets as shape retrieval contest (SHREC 2009) [5] of partial 3D models for evaluation. The query set consists of 20 partial models obtained by cutting parts from complete models. Both of the query datasets contain one example for each class, as shown in Fig. 2. The target datasets contain 720 models categorized into 42 classes.

Fig. 2: List of parts query dataset.

Two sets of 6-view and 18-view depth buffer images of resolution 256×256 are generated respectively for comparison. The 6-view is rendered from vertices of an octahedron and 18-view is generated from a 32-hedron with respect to 90 degrees rotations about the three orthogonal axes. In the original salient sampling, the average numbers of features for 6-view and 18-view representation are 447 and 1,231 respectively. For dense sampling, the bin size is choosen as 16 and sampling step is 8 and 16 respectively, which could generate 1,014 and 3,042 features. For pyramid sampling, we let the bin size to be [4 8 16 32] and sampling step to be 16, which results in 3,492 features for 6-view and 10,467 features for 18-view representation.

Retrieval accuracy is evaluated using nearest neighbor (NN), first tier (FT), second tier (ST), discounted cumulated gain (DCG), and mean average precision (MA), respectively. The results are summarized in Tab. 1 and Tab. 2.

<table>
<thead>
<tr>
<th>Method</th>
<th>NN</th>
<th>FT</th>
<th>ST</th>
<th>DCG</th>
<th>MA</th>
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<tbody>
<tr>
<td>S6</td>
<td>0.10</td>
<td>0.139</td>
<td>0.239</td>
<td>0.453</td>
<td>0.141</td>
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<td>D6_S16816</td>
<td>0.30</td>
<td>0.183</td>
<td>0.278</td>
<td>0.486</td>
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<tr>
<td>D6_S8B16</td>
<td>0.20</td>
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<td>0.161</td>
<td>0.421</td>
<td>0.096</td>
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<td>P6</td>
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<td>0.158</td>
<td>0.437</td>
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<table>
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<tr>
<th>Method</th>
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<th>ST</th>
<th>DCG</th>
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<tbody>
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<tr>
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<tr>
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<td>0.317</td>
<td>0.515</td>
<td>0.206</td>
</tr>
<tr>
<td>P18</td>
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<td>0.156</td>
<td>0.247</td>
<td>0.466</td>
<td>0.164</td>
</tr>
</tbody>
</table>

The results shown above suggest that retrieval accuracy for 18-view depth buffer images is better than that of 6-view depth buffer images. However, for both 6-view or 18-view depth images, the dense sampling with bin size of 16 and sampling step of 16 achieves the best results overall, although pyramid sampling and S8B16 have more features than it. This leads to the conclusion that more features do not guarantee better retrieval accuracy for 3D partial models. Rather, how the features are sampled is more significant and influential.

Conclusions

In this paper, we propose the optimal sampling strategies to extract local salient features for 3D partial model retrieval using the bag-of-words model. Results conducted on SHREC 09 parts dataset demonstrate that dense sampling with bin size and sampling step of 16 achieved higher-retrieval accuracy, although other sampling methods may have extracted more features than this. This leads to the conclusion that more features do not guarantee a result in higher efficiency, while the choice of feature extraction parameters is also important than other factors.

References
Extended Abstract 19

Title
Preprocess-Optimization for polypropylene laser sintered parts

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Keywords
Rapid Prototyping, Additive Manufacturing, Laser-Sintering, Part orientation, Build direction

Introduction
Additive Manufacturing (AM) refers to a group of technologies used for producing prototypes (Rapid Prototyping), tools and molds (Rapid Tooling) and end products (Rapid Manufacturing). Due to the additive process which builds up the physical part layer by layer, geometries of any complexity like undercutts and internal features can be built, because the whole geometry of the part is not of importance in the current layer. So during the last years AM is successfully used as an effective tool for the rapid development of products of nearly any complexity [1, 2].

Every AM process is characterized by the preprocessing, the build process and the postprocessing [3]. Common for all layered manufacturing techniques is that part-quality and manufacturing costs depend on the part orientation during the process. The result is that different parameters must be balanced in order to find a good orientation for each part. Based on the “optimal” orientation, the different parts are positioned inside the build chamber of the AM machine. Hence, the orientation of parts is influenced by several different parameters, difficulties occur when the best orientation has to be found. State of the art software does not deliver adequate solutions for this problem. Therefore, the user has to identify good part orientations based on his experience. Here a number of orientation-dependent effects such as stair-stepping, anisotropic material properties like mechanical strength and shrinkages must be considered for the correct choice of part orientation. Usually this circumstance can be reduced by selecting suitable process parameters (laser beam power, scan speed) and building strategies (scan strategy, shrinkage compensation). Additionally the consideration of the AM process within an economic point of view becomes increasingly important. Beside the fixed costs, such as capital, labor and maintenance costs, the variable costs (material and operating costs) are significantly responsible for the total costs. For that reason the selection of the part orientation must be considered as part of the total construction costs, which are reflected in both - the building time and the wasted powder.

All in all, the procedure of the correct orientation becomes more and more difficult with increasing part complexity and necessitates increasingly computer-based tools.

Main Idea
Preliminary findings show, that the powder bed temperature, the power of outline and fill laser, the scan speed, the fill scan spacing as well as the layer thickness are significant parameters for laser-sintered part properties [4-6]. Here the mechanical properties rise as a function of the energy density of the laser. Simultaneously the geometric specifications, such as the surface roughness or the dimensional accuracy get worse with a high energy density. Illustrated researches examine just the influence of process parameters and orientation to single quality values. Research, related within this paper carries the studies forward by a simultaneous optimization of the process parameters for different target values. The development of multi-objective optimization strategies are supposed to ensure a part orientation, which considers manufacturing and functional aspects based on previous findings [7, 8]. Subsequently the task of the paper can be subdivided into the following two problems:

Process Optimization. Initially the main influencing factors of the laser-sintering process for defined quality characteristics have to be identified. Therefore several test geometries were designed to perform the measurement tasks (Figure 1).
In the course of investigations eight different parameters which are varied in four different levels will be chosen for the analyses. To perform the analyses, the robust design method of Taguchi is used. Here not all possible combinations of the chosen process parameters, but a selected subset were performed, without reducing the information value of the analyses [4]. In this case, the array $L_{32}$ was chosen. To analyze the results, two different evaluation methods were used. First the signal-to-noise (S/N) is used to identify the best parameter settings. Second the analysis of variance (ANOVA) is used to identify significant factors. As a result of this chapter the laser-sintering process shall be optimized under the consideration of the relationship between the process parameter, the part orientation and the part properties.

Part orientation. Based on the findings of the process optimization, a multi-objective approach for the part orientation is developed. Therefore the identified effects for part quality and process efficiency are taken into account. Adapted from this input parameters, a genetic algorithm is used to determine the optimal orientation. Starting with a preparation step, the part geometry is imported as STL file, then the convex hull is constructed and extreme dimensions are determined. Subsequent the genetic algorithm is initialized. Then, the part is rotated in different angles and for each orientation the part is sliced and evaluated for the identified effects like volume, cusp height, build time, max. exposure area, etc. The combination of this effects result in a fitness analysis for each examined orientation. As long as this function does not reach convergence a recombination, mutation and selection of a new population leads to a new calculation. When the fitness analysis reaches convergence, the suggested orientations are exported as STL files in the new orientation.

Conclusions
The results of all experiments have proven that the part orientation influences the part quality and the process efficiency. Nevertheless, useful tools for a software-based automation of this pre-process step are not available for the user today. This may go along with time-consuming evaluation of the influencing parameters for the different AM processes and machines. However, the experiments have proven that parameter-based automated part-orientation optimization is possible.

References
Extended Abstract 20

Title
Particle Swarm Optimization (PSO) Based Topology Optimization of Part Design with Fuzzy Parameter Tuning

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Keywords
Particle swarm optimization (PSO), Fuzzy logic, Topology optimization, Part design

Introduction

Structural topology optimization is a complicated and multi-objective oriented optimization method used frequently for both structural and mechanical part design. Briefly speaking, topology optimization attempts to achieve one or multiple objectives subject to several pre-defined constraints. Obviously constraints play a very important role in the optimization process. In traditional mathematical solution, constraints are expressed as strict criteria, however, the optimization algorithm or the optimization problems themselves are usually complicated and uncertain in practice, a clear set of constraints seems not truly reflect practical situation. Take an actual structural optimization problem as an example, the optimization may consider both the material weight constraint and a set of manufacturing constraints. The correlation and effect of these two types of constraints are uncertain and unknown. A clear set of the effect of these constraints will cause man-made interference to the optimization results. Even under a single constraint, a clear set of constraint is still questionable for evolutionary based optimization algorithm. The reason is that evolutionary algorithms themselves are based on a natural selection process. Strict criteria may throw out potential candidates who slightly violate the pre-defined constraint at the beginning of optimization process. To solve the problem of uncertainty, vagueness, and application dependence of optimization constraints, fuzzy logic is introduced into the PSO-based topology optimization method.

As a potential topology optimization method, Particle Swarm Optimization (PSO) is an evolutionary algorithm which was first reported by Kennedy and Eberhart [1]. This method attempts to mimic the social behavior of bird flocking. In a previous study by the authors [2], the performance and efficiency of PSO in topology optimization is found to lag behind traditional topology optimization algorithms such as the Solid Isotropic Material with Penalization (SIMP) method [3]. In previous studies, there were several modifications on PSO to improve its performance and efficiency [4] [5]. However in traditional PSO and those modified PSO schemes, a pre-defined crispy material weight constraint is normally used. This strictly tightens search space. After introducing fuzzy parameter tuning into PSO, the candidate solutions slightly violating constraints during the early optimization process will be reserved, since they still stand a chance to obtain the optimal solution in subsequent iterations. As a result the search space of PSO will be more flexible, the global search ability of PSO will be improved after using fuzzy parameter tuning. On the other hand, the search efficiency of PSO will be improved simultaneously because knowledge and experience about the PSO process represented as fuzzy membership functions will help PSO to run in an intelligent way and thereby increase the search efficiency.

In this study, the fuzzy tuning of a single constraint PSO problem will be developed mathematically first. One illustrative example is used to validate the proposed method. By comparison, the PSO with fuzzy parameter tuning is found to have better search performance and higher search efficiency.

Main Sections
PSO simulates the behavior of a bird flocking. Each bird in the flock continually processes information of its current position and velocity. When applied to topology optimization problems, the relative densities \( \rho \) take the place of positions, and the incremental change of relative densities replaces velocity. After these arrangements, the minimum compliance problem of topology optimization based on PSO could be formulated as:

\[
\begin{align*}
\min \ c &= f^T u \\
\text{s.t.: } V_s &\leq \overline{V}
\end{align*}
\]

(1)

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
Here c is the compliance of structure, f, u and K are the load, displacement and stiffness matrix of structure respectively. Vs and V bar are practical material volume and pre-defined volume constraint. Assume a flock has p particles, for particle d, the PSO updating schemes for both velocity change and density change are expressed as:

\[
v_{k+1}^d = v_{k}^d + c_1 r_1 (p_k^d - p_{k}^d) + c_2 r_2 (p_g^d - p_{k}^d)\\
\rho_{k+1}^d = \rho_{k}^d + v_{k+1}^d
\]  

(2)

Here k is the time increment; w is an inertia weight; p_g is the best ever densities in the swarm. p_k is the best previous density of particle d at time k. The explanations of all symbols, the detail of volume constraint, and the checkerboard control method could be found in [2].

As mentioned above, the traditional PSO scheme uses a pre-defined material volume constraint V bar in equation (1). Due to the drawbacks as mentioned in the introduction section, a fuzzy logic controller is introduced. Equation (1) is modified with fuzzy constraints as below:

\[
\min \ c = f^T u \\
\text{s.t.:} \ V s \leq \tilde{V} + \tilde{V}^c
\]  

(3)

Here a fuzzy constraint V tilde is used. The symbol tilde is used to indicate that the constraint contains fuzzy information. \( \tilde{V} \) is the extended tolerance of the fuzzy constraint. Unlike traditional mathematical logic divides object into yes or no (0 or 1), fuzzy logic utilizes membership functions to represent the degree of belonging of object from 0 to 1. Because fuzzy logic could utilize human reasoning to make decisions, the degree of belonging could be described by a series of linguistic terms [6]. Take the minimum compliance problem as an example, the material volume is described as “very small”, “small”, “medium”, “large” and “very large”. According to the input range and definitions of membership functions, the fuzzy input is calculated. This process is called “fuzzification”. The detailed definitions of membership function will be presented in the full paper. Based on fuzzy rules which will be described in the full paper, the fuzzy output will be determined. Finally a defuzzification process is used to obtain a numerical output. By using this fuzzy logic controller in PSO, the risk of premature solutions and loss of potential solutions in traditional PSO could be reduced. Meanwhile because human reasoning and experience could be adopted in membership functions, PSO with fuzzy tuning could search the optimal solutions in an intelligent and efficient way.

Conclusions

After comparison by sample studies, the fuzzy logic is validated to be feasible and effective in PSO-based topology optimization. The fuzzy constraint could more accurately reflect the actual optimization process. The PSO based topology optimization with fuzzy parameter tuning has better search ability and higher search efficiency than that of traditional PSO.

References

Extended Abstract 21

Title: Analysis and Evaluation of Limb Alignment in Total Knee Replacement.

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Keywords: Total knee replacement, limb alignment, point cloud technique, 3D reconstruction, finite element analysis.

Introduction
Numerous factors contribute to success of a total knee replacement (TKR); including surgical instruments, operational methods, positioning of prosthesis, limb alignment, cementing techniques and surgical experience [1-2]. The technical objective of total knee replacement surgery is to replicate the ‘new’ alignment and it is achieved during the surgery through precise and orchestrated surgical steps. Femoral mechanical axis (FMA) is a straight line drawn from the femoral head to the middle of intercondylar region and tibial mechanical axis (TBA) from tibial plateau to center of ankle as shown in Fig. 1 (a) [3-4]. Both normally aligned mechanical axes represents the straight line drawn from the center of the femur head to the center of the ankle which passes through the center of intercondylar region of the knee i.e. entire limb in standing position from hip to ankle which is also considered as load bearing axis (LBA) of the body. Overall alignment is the angle made by femoral axis with the tibial axis in the coronal plane.

Fig. 1: (a) Frontal view of normal limb alignment after TKR showing load bearing axis (LBA). (b) 3° medial deflection of FMA disturbing normal LBA, known as varus deformity. (c) 3° lateral deflection of FMA disturbing normal LBA, known as valgus deformity.

The alignment positions are depending on the articulating plane which is referred to mate the femoral component with the tibial polyethylene plate. In the coronal plane, femoral and tibial cut lines decide the accuracy of the articulating plane. If FMA is making an angle 90° with articulating plane, then it is said as normal alignment otherwise it develops varus and valgus deformities as shown in fig. 1(b) and fig. 1(c) respectively. These can be partially overcome by releasing or tightening the ligaments. Limb alignment has been studied clinically. Alignment range ±3° improves longevity of total knee arthroplasty. However these alignment boundaries still remain a hypothesis, as ±3° is an arbitrary value; therefore need validation. In this work, the main objective is to analyze the pattern of relative stress distribution in TKR if the axial alignment is gradually increased or decreased including the range of ±3°. Optimum alignment angle may further reduce the time for ligament balancing.
Main Idea

The work emphasizes evidence based good limb alignment position in TKR. This work shows an application of digital modeling of limbs and implants where CAD has been applied to design the assembly of femur, tibia and knee implants. The process starts with generation of point cloud definition of the implants. The point cloud data are registered and processed; B-spline curves are fitted on to the point cloud of the implant. The bone models are obtained from volunteer’s CT scan images via segmentation, region growing and mesh processing followed by 3D reconstruction of femur and tibia. The work flow framework is shown in Fig. 2.

The assembly modeling of femur, tibia and knee implants is investigated with finite element method. The tibial plate bottom is constrained with all degrees of freedom and 2600N load is applied to the center of femoral component considering standing position. The analysis is carried out at different alignment positions in Ansys workbench 14.0.

![Fig. 2: Analysis of limb alignment work flow framework](image)

Conclusions

The model investigates that the von mises criterion, normal stress vary across the components in different alignment positions. Within ±4° the rise in stress across the model surfaces is not much; however beyond ±5° the relative pressure distribution across the articular interface drastically rises to show the pressure imbalance with every degree of change. This investigation is valuable for surgeons in TKR surgeries and possibly underlines the importance of use of computer assisted surgeries to obtain more accurate alignment and more ever to avoid the outliers outside ±5°.

References

Extended Abstract 22

Title
High-quality approximation technique for two offset surfaces adjoining with $G^1$-continuity

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Keywords
Offset Surface, Surface Approximation, $G^1$-Continuity, $C^1$-Continuity, Bicubic B-spline Surface

Introduction
Surface offset is an important operations in CAD and various applications. Since the face of a three-dimensional model is usually constructed by multiple rational parametric surfaces, offset surfaces are required for the operation. If two surfaces are $G^2$-continuous, the offset surfaces of those are also $G^2$-continuous [3]. However, a spline approximation of offset surfaces is widely used because offset surfaces are in general not rational representation [2].

Offset surfaces are often given to numerical calculation of first order differential equations, such astrace calculation of blending surfaces or tracing intersection between surfaces. Thus, approximated surfaces are tractable if they are at least $C^1$-continuous. Several methods for approximating offset surfaces with at least $C^1$-continuous spline surfaces have already been presented [2,4,6]. However, none of those methods consider the continuity of adjacent offset surfaces because they generate offset surfaces individually. Therefore, gaps or creases arise between two approximated surfaces when two $G^1$-continuous offset surfaces are approximated using the methods. The portion in an oval with broken line in Fig.1 is an example of gaps. $G^1$-discontinuity caused by such as gaps or creases lowers shape data quality because it incurs data conversion failure [5].

Thus, this paper proposes a technique for a $C^1$-spline approximation of offset surfaces considering continuity of adjacent offset surfaces. Our technique can generate approximated offset surfaces which are higher quality than existing methods because no gaps or creases arise between approximated surfaces, when two $G^1$-continuous offset surfaces are approximated.

![Fig.1: (a) Gap between approximated surfaces, (b) Subdivision of parameter domain of offset surfaces, (c) Control points on the common boundary and ones on both sides of the common boundary.](image)

Main Idea
We propose a technique for approximating two $G^1$-continuous offset surfaces that generates two $G^1$-continuous approximated surfaces represented by $C^1$-continuous bicubic B-spline surfaces. The technique consists of the following three steps. In step 1, approximate each of the offset surfaces piecewise with bicubic Bezier patches. The patches are generated so that two adjacent those are $C^1$-continuous except those existing along the common boundary between the offset surfaces (or merely referred to the common boundary). In step 2, adjust control points of the patches existing along the common boundary so that two adjacent those on the common boundary are $G^1$-continuous and those along the common boundary are $C^1$-continuous. In step 3, generate two $C^1$ bicubic B-spline surfaces by combining the patches. The outlines of steps 1 and 2 are described below.

Step 1: First, approximate each of subdivided domains of two offset surfaces with a bicubic Bezier patch, in a similar manner to Hoschek’s method[4]. Next, adjust positions of control points of the patches using Beeker’s method[1] so that two adjacent those are $C^1$-continuous except those existing along the common boundary. Then, if the patches are not adjoining to be one-on-one on the common boundary as the result of the approximation, subdivide the parameter domains so that two sets of division points along the parameter interval of the common boundary coincide with each other. Red bold line in Fig.1 (b) shows an
example of the subdivision. After that, reconstruct a patch for each of the subdivided domains, and adjust positions of control points of the patches again.

Step 2: adjust control points of the patches existing along the common boundary so that two adjacent those on the common boundary are $G^2$-continuous and those along the common boundary are $C^1$-continuous. The control points to be adjusted are those on the common boundary except the corners of the patches, and those beside the common boundary. Fig.1 (c) shows the control points to be adjusted; black dots show those on the common boundary and the white dots show those beside the common boundary. These control points are moved as slightly as possible so that given constraint conditions of continuity are satisfied. To be more specific, the control points after the adjustment are determined by the equation below when $n$ control points constraining each other are adjusted simultaneously:

$$
\sum_{i=1}^{n} |P'_i - P_i| \rightarrow \min .
$$

where $P_i$ are the control points before the adjustment and $P'_i$ are those after the adjustment. To these control points, our original two constraint conditions which enable patches to satisfy $G^2$- and $C^1$-continuity simultaneously are given, in addition to the constraint conditions guaranteeing $G^2$- and $C^1$-continuity individually. The first constrains a pair of two cross boundary derivative vectors at each corner of the patches on the common boundary (arrows in Fig.1 (c)). To be more specific, the ratio of the size of the one vector to the size of the other in the direction of the mate is constrained. The second constrains the pairs except for both ends of the common boundary so that two vectors are collinear. As the result, two patches adjacent on the common boundary are $G^2$-continuous and those along the common boundary are $C^1$-continuous.

Fig.2 is an example of applying the technique described in this paper. Fig.2(a) shows the three-dimensional model in the shape of bottles. Fig.2(b) shows two $G^2$-continuous bicubic Bézier patches of the model. Fig.2(c) shows the result. Fig.2(d) shows the control points of the approximated offset surfaces rendered in Fig.2(c). Fig.2(e) shows the bicubic Bézier patches which are combined to the bicubic B-spline surfaces depicted in Fig.2(d). Fig.2(f) is the enlarged view of Fig.2(e) along the common boundary, and shows the normal vectors of the approximated offset surfaces along the boundary curves. As shown in Fig.2(f), no gaps or creases appear between the approximated offset surfaces.

Fig.2: (a) 3-D model, (b) Two $G^2$-continuous surfaces of (a), (c) The result, (d) Control points of the approximated offset surfaces, (e) Bicubic Bézier patches of (d), (f) Enlarged view of (e) along the common boundary with normal vectors.

Conclusions
In this paper, we proposed a technique for approximating two $G^2$-continuous offset surfaces that generates two $G^2$-continuous approximated surfaces represented by $C^1$-continuous bicubic B-spline surfaces. The approximated surfaces are higher quality than those generated using existing methods, because no gaps or creases arise between the surfaces. Furthermore, because the approximated surfaces are $C^1$-continuous, those are tractable in numerical calculation of first order differential equations, such as tracing the calculation of blending surfaces or tracing intersection between surfaces.

References
Extended Abstract 23

Title
A Study on Parametric Shape Modifications of 3D Skeletal Models

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Keywords
Bio-Mechanical Models, Parametric Models, Shape Deformation

Introduction
Biomechanical models of the human body, and in particular parametric human models have a wide range of applications. There are various factors that make construction of such models difficult. These include the difficulty to model free form shapes, large shape variations, poor models for soft tissues, etc. An important step towards achieving a solution is to generate parametric skeletal models.

In this paper, we introduce a new method to parametrically define shapes of skeleton components (bones). Our approach has several advantages: we require only a few sample bones of a class to construct a fairly robust template model; our approach does not rely on accurate identification of specific landmarks or shape features; finally, our algorithms are robust and efficient. The main tool we use is free form deformation (FFD), which we use to modify the shape of a template mesh by dislocating its affiliated lattice, which itself is automatically derived by mesh simplification. This template bone is automatically deformed to match the shape of different samples, given just a few parameter values as input. We also evaluate the accuracy of the model and analyze the performance of our approach under different settings.

Main Idea
At a high level, suppose that we wish to construct the model of a particular human, say, for estimating the comfort level of a pair of shoes that is designed for her. Scanning technologies such as MRI or CT may be employed, but are clearly too expensive for such purposes. On the other hand, a small set of measurements (such as the length of the foot in a flat, load-bearing posture) yield too little information for an accurate model. Our approach is based on the premise that we can construct a much more accurate model by using the relatively safe, inexpensive, and fast technology of laser scanning. Thus our long term goal is to automate the task of converting a laser scanned shape model to generate a full-scale parametric model that can be used to perform operations such as posture changes, static force analysis, motion simulation etc. In this paper, we only focus on a small component of this problem, namely, the generation of a parametric model of a single bone from a skeleton.

An informal problem definition follows. We are given the geometric shape of a set of bones, \( B_i, i = 1..n \), (e.g. the first metatarsal bone), one from each individual of a sample from a population. Using this sample, we wish to (a) identify/generate a nominal (i.e. a template, or exemplar) geometric model, \( T_a \) of such bones over the entire population; and (b) identify a small but sufficient set of parametric measurements, \( p_{B1}, \ldots, p_{Bk} \), and a simple mapping, \( f(p_{B1}, \ldots, p_{Bk}) : T_a \rightarrow B \) that can be used to accurately map the template model to the geometric model of an unknown shape for which we know only the parameter values. Clearly a solution to this problem is essential in solving our long-term problem of parametric skeleton models.

The following Figures show flow charts of the algorithms that we implemented, and will present in the full form of this paper. The algorithms in these stages build on some existing geometric tools. For example, to align the model samples into a common global coordinate frame, a simple iterative algorithm that minimizes the Hausdorff distance between a pair of meshes, defined as: Hausdorff distance. A key feature of our approach is that we do not require user input in identifying specific geometric shapes, or features, on a given bone (in other words, we do not use notions like semantic features). Instead, we use a mesh decimation algorithm (Quadric Edge Collapse Decimation) to generate a representative, simplified polyhedral representation of the template bone; the vertices of this simplification are used as a control mesh that is then used to determine a small set of parameter values describing it, and therefore the geometry of that bone. Other instances of the bone model can then be generated by varying these parameters. The algorithm used to modify the template model shape by changing of the parameter set (i.e. by changing the control mesh) is an adaptation of the t-FFD (Triangular Free Form Deformation) method.

The approach above was implemented, and tested on two sets of bone samples. The first was a set of metatarsus bones of chickens. Half of sample set was used to construct the parametric models. For each sample from the second half, a small set of measurements were used to estimate the parameter values, which were then used to modify the geometry of the template

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
model. The error analysis between the predicted model and the scanned model of the test sample provided a measure of the efficacy of our approach. To verify our approach for different shapes, we also tested the approach with a series of samples of femur bones of pigs. The figure below indicates the error analysis between the parametric and the measured shapes of two bones used in our experiments.

References

Fig. 1: (a) Flow chart showing the stages of construction of a template model from a set of bones representative of a population; (b) Flow chart showing how a model instance can be generated from a given template and a set of measurements that allow estimation of parameter values.

Fig. 2: Prediction accuracy of (a) chicken metatarsus (2) pig femur. Only red zones have error > 2mm.
Extended Abstract 24

Title: Determining curves in the convex hull from a set of planar freeform closed convex curves

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Keywords
Convex hull, freeform curves, minimum spanning tree

Introduction
Convex hull [3] of a set is defined as a minimal area convex enclosure of the set. Quite a few algorithms exist for computing the convex hull of a point set [3], both in $R^2$ as well as in $R^3$. Convex hull has found numerous applications, ranging from interference checking to shape matching.

Convex hull typically imply that it consists of not just few elements from the set but also which elements are connected. For example, convex hull of a point set is typically a convex polygon (consisting of both points and connecting edges). Moreover, in some applications such as positive α-hull, only points on the convex hull play a role and hence it may be sufficient to determine them.

Problems such as convex hull are usually considered for a set of points, and belong to the filed known as computational geometry. Fields such as CAD, geometric modeling which deal typically with domains like closed curves and surfaces are now being used as input to study problems such as art-gallery, medial axis, Voronoi cell etc. Inputs such as curves also call for different kind of approach for the same problem for a set of points. For example, for the computation of convex hull of a set of curves, tangents and bi-tangents computations are required [2]. The computations are typically much more numerically intensive than its point-set counterpart.

To the best of the knowledge of the authors, very few algorithms compute the convex hull for a set of curves represented exactly (i.e. without approximating the curves using sample points). An algorithm for computing the convex hull of a set of freeform curves has been provided in [2]. Moreover, Delaunay triangulation (whose boundary is the convex hull) for a set of curves is not well known. Approach using sampling of points from the curves will result in a very coarsely approximated hull. In this paper, an algorithm for computing the curves that belong to the convex hull has been presented.

Main idea
Let $S$ be a set of disjoint free-form (parametric) convex curves (curves without inflection points) with no straight line portions and having no discontinuities in $R^2$. As the set of curves are disjoint, minimum spanning tree (MST) is used to make connectivity between them. Computing minimum distance between the curves and then using prim’s algorithm, MST is obtained. The edges in the MST act as a part of a rubber band that enclose the curves. MST also guarantees that no other edge obstruct the edge between two curves. For the adjacent curves in MST, the triplets of each of the curves form a triplet matrix (TM). A curve in a MST is split into segments equal to the valency (i.e. number of MST edges attached to it) of the curve. For each triplet, the adjacent edges are then dilated to form a new edge using the minimum radius of maximal inscribed circle (MIC, maximum radius circle that touches all the curves). However each time the dilation is performed, a portion of the curves is left from further computation. The triplet matrix is updated using Algorithm 1. Updating step is terminated when there is no triplet remaining for further processing. Algorithm 2 presents steps to get the curves in the convex hull from $S$. Figure 1 illustrates the algorithm. It is to be noted that an algorithm for convex hull of a set of points need not return the points in the convex hull in an ordered manner [3]. In this paper, the output from the algorithm gives the connectivity information of the curves forming the convex hull of the set.

Algorithm 1 UpdateTM(TM, $[C_2C_3C_4]$)

if The pair $[C_2C_3]$ is present in the triplets under $[C_4]$ then
    Replace the triplet $[C_2C_3C_4]$ by $[C_2C_3C_6]$
end if

if The pair $[C_2C_4]$ is present in the triplets under $[C_3]$ then
    Replace the triplet $[C_2C_3C_4]$ by $[C_2C_1C_6]$
end if

Delete $[C_2C_3C_4]$ from TM.
Algorithm 2 CurvesInConvexHull(S)

```
TM=nil
PM=nil.
MST=MST(S).
TM=TripleMatrix(MST).
while TM ≠ NULL do
  for Each element in TM do
    Find MIC (Maximum inscribed circle)
  end for
  if Number of MIC ≠ 0 then
    Circ_{min} = Minimum (MIC).
    Let [C_i C_j C_k] be the triplet corresponding to Circ_{min}
    Call Update TM(TM,[C_i C_j C_k])
  else
    for Each Element T_a in TM do
      Split T_a = [C_i C_j C_k] into [C_i C_j] and [C_j C_k] and add to PM
      delete T_a
    end for
  end if
end while
for Every pair [C_i C_j] in PM do
  Merge the pairs to get curves in the convex hull
end for
```

Fig.1: Dilation of MST edges in the algorithm.

Results and discussion
Implementation of the algorithm (Algorithm 2) has been carried out using IRIT [1], a solid modeling kernel. Figure 2 shows the set of curves with MST in the top row with corresponding output (curves in the convex hull in the bottom row). Algorithm 2 runs in O(n^2 log n) in the worst case. Correctness and completeness of the algorithm have been proved.

Fig. 2: Test results showing MST (top row) and the curves in the convex hull (bottom row).

Conclusion
In this paper, an algorithm for determining curves that belong to the convex hull from a set of planar closed disjoint curves based on MST computation. It has been shown that the curves in convex hull can be obtained without geometrical structures such as Voronoi diagram or Delaunay triangulation, that are traditionally proven to be difficult to compute for curves. The curves are assumed to be simply-connected convex curves, having no straight line portions and no discontinuities. Results indicate that the algorithm is very amenable for implementation. Possible future work can include GPU-based computation and also handling of intersecting curves.

References
Extended Abstract 25

Title
Type-Constrained Direct Fitting of Quadric Surfaces

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Keywords
Reverse Engineering, Surface Fitting, Quadrics, Ellipsoids, Cylinders, Cones, Hyperboloids, Paraboloids, Rotational Symmetry

Introduction
Efficient fitting of quadric surfaces to unstructured point clouds or triangle meshes is an important component of many reverse engineering systems [6]. Users may prefer a given surface be fit by a specific quadric type: for example, they may want to ensure the quadric is a cone, ellipsoid, or a rotationally-symmetric subtype (spheroid, circular cone, etc). Methods for type-specific quadric fitting are scattered throughout the literature: some papers handle spheres, circular cones and cylinders [5]; a few others handle ellipsoids [7] or hyperboloids [1]; non-circular cones and general rotationally symmetric quadrics are not typically discussed. In this paper, we present a thorough catalog of type-specific quadric fitting methods, including new methods that handle neglected quadric types, and improvements to previously proposed methods for ellipsoid- and hyperboloid-specific fitting methods.

Main Idea
Because fitting quadric surfaces is a non-linear problem, efficient quadric-fitting methods typically work in two steps: (1) a linear, direct method (typically an “algebraic” fitting method) generates an initial guess and then (2) a non-linear, iterative method is used to refine that guess [3,5]. Chernov and Ma presented efficient, non-linear optimization techniques to handle the non-linear optimization step for any quadric type [3]. The remaining challenge is the first step: generating an ‘initial guess’ that matches the desired quadric type, and is as close as possible to the error-minimizing result. We present direct fitting methods to quickly generate accurate initial guesses for a complete catalog of quadric surface types. Our catalog includes hyperboloids, ellipsoids, elliptical/hyperbolic paraboloids, elliptical/parabolic/hyperbolic cylinders, general cones, planes, and the rotationally-symmetric quadric sub-types (such as spheres, spheroids and circular cones).

All methods in our catalog use the basic framework of Taubin’s method for algebraic surface fitting: Given some implicit formula for a quadric \( f(p) = 0 \), solve a small generalized eigenvalue problem to minimize the squared algebraic distance \( \sum f(p_i)^2 \) under the normalization \( \sum \| \nabla f(p_i) \|^2 = 1 \) [8]. Taubin’s method has very low fitting bias, and has been established as one of the most effective direct fitting methods in practice [2,3].

Our fitting methods handle a wide range of quadric types with just two high-level strategies. In the first part of our paper, we show how quadratic constraints and a closed-form line search in parameter space allow us to effectively fit hyperboloids, ellipsoids, and paraboloids. In the second part, we show that transforming the problems to more convenient spaces and reducing the parameters used in fitting allows us to handle all remaining cases.

Fitting Method for Hyperboloids, Ellipsoids, and Paraboloids. Previous direct fitting methods for ellipsoids and hyperboloids have replaced Taubin’s normalization with type-specific normalizations that ensure the result has the desired quadric type [1,7]. These methods guarantee a hyperboloid or ellipsoid, but the type-specific normalizations introduce more bias than Taubin’s method, leading to poor results for data with even small noise (Fig. 1c). We improve upon these methods by taking the best results of previous approaches and using a direct method (derived from [4]) to search a linear subspace of those results for a better result. We also show that, when Taubin’s method does not return a quadric of the desired type, the best quadric of that type (under Taubin’s metric) must be on the type’s boundary: e.g., if we want to fit a hyperboloid and Taubin’s method returns an ellipsoid, then the best hyperboloid is within \( \epsilon \) of a paraboloid (Fig. 1b). Therefore, we show that ellipsoid- and hyperboloid-specific fitting is equivalent to paraboloid-specific fitting. We fit all three quadric types with the same framework.

Fitting Methods for Lower-Dimensional Quadric Types. The remaining quadric types all exist in lower-dimensional sub-spaces of the full 9-dimensional space of quadrics [6]. The key to efficiently fitting these quadric types is to express the quadric with fewer parameters, such that only quadrics of the specified type can be generated, and then apply the standard algebraic fitting procedures on that parametrically-reduced form. For example, for planes and spheres we can simply drop and combine terms.
from the standard implicit quadric function to arrive at a plane- or sphere-specific function (e.g. \( f(x, y, z) = a(x^2 + y^2 + z^2) + bx + cy + dz + e \) for spheres).

For most other lower-dimensional quadrics, the required low-dimensional space is more complicated: for example, there is no known linear-least squares method to fit circular cones and cylinders to a point cloud using just point positions [6]. However, there are linear-least squares methods for fitting such shapes to point clouds with normals [2,5]. For dense point clouds and polygonal meshes we can estimate normals (e.g. by local plane fitting, or averaging triangle normals), and then use a two-step process to fit the quadric. First, we estimate key parameters of the quadric using a direct “kinematic surface fitting” procedure that can determine properties such as a rotation symmetry axis (for a rotationally symmetric quadric), the direction in which the shape does not change (a cylinder axis) or the central point of scaling (for a general cone) [2]. Second, we transform the data to a more convenient space, and we perform the standard algebraic fit in that space. In the transformed space, it is possible to reduce the quadric parameters as we did for planes and spheres. For example, to fit general cones we translate the data so that the cone apex is at the origin, and then fit a quadric with the linear and constant parameter terms dropped: \( f(x, y, z) = ax^2 + by^2 + cz^2 + dxy + exz + fyz \) (Fig. 1g).

![Fig 1: Examples of quadric fitting (result in red) applied to a noisy data (blue mesh). (a) General quadric fitting using Taubin’s method fits an ellipsoid; we use this as our ellipsoid-specific fit. (b) Our hyperboloid-specific fit; it is also within \( \varepsilon \) of our best paraboloid-specific fit. (c) The hyperboloid-specific fit of Allaire et al. [1] has significantly higher error. (d) General quadric fitting applied to a noisy hyperbolic paraboloid results in a hyperboloid. (e) Our direct hyperbolic paraboloid fit finds an exact hyperbolic paraboloid. (f) General quadric fitting applied to a noisy cone results in a hyperboloid with a non-zero neck at the top. (h) Our cone-specific fitting produces an exact cone.](image)

**Conclusions**

We provide a practical guide for type-specific quadric fitting. We show that two straightforward, high-level approaches are general enough to fit a large range of quadric types. Our methods for ellipsoids and hyperboloids improve the state of the art, while our methods for paraboloids, general cones and rotationally symmetric quadrics fill gaps in the literature. We show results that demonstrate our methods give reasonable fits in practice.

**References**


Extended Abstract 26

Title:
Reconstruction method of trimmed surfaces with maintaining $G^1$-continuity with adjacent surfaces

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Keywords
Trimmed Surface, Surface Fitting, Notch Shape, $G^1$-continuity

Introduction
The surface fitting method to N-sided regions is the important fundamental technology in geometric modeling and is used for various contents. The trimmed surface compression method[2] that the authors proposed last year is based on the surface fitting method and we succeeded in compressing trimmed surfaces efficiently. Although the surface fitting method[1] currently used in [2] is applicable to concave shapes or shapes with holes, the method can connect surfaces with $G^1$-continuity only in one direction or in opposite directions. Many analytic surfaces like cylindrical ones are contained in CAD data like machine parts. In many cases, such surfaces become $G^1$-continuous with an adjacent surface in one direction or in opposite directions, and the method[1] can express most of surface shapes. In the 3D models with trimmed surfaces shown in Fig.1 (c), however, there is a surface whose boundary edges are connected with adjacent surface with $G^1$-continuity. Especially in 3D models with artistic designs such as automobiles or motorbikes, a lot of surfaces are $G^1$-continuous in two adjoining directions. The method[1] is inapplicable to such shapes.

In this paper, the method[1] is extended and the surface fitting technique is proposed for a closed region where the boundary edges connect with adjacent surfaces with $G^1$-continuity, as shown in Fig.1 (c). In the proposed method, boundary edges are input and surfaces are output. Two surfaces are connected with $G^1$-continuity by using the control points at the connection section obtained from cross boundary derivatives. In addition, the control points in the region or on the discontinuous boundaries are obtained by approximating sample points, and the proposed method can also be applied to concave shapes or shapes with holes appearing frequently in CAD data.

![Fig.1: (a) CAD data, (b) Trimmed surface and effective region taken out from (a), (c) Concave shape $F$ that has adjacent $G^1$-continuous surfaces $F_2$ at the top and $F_1$ in the left, (d) Concept of surface fitting for the closed region.](image)

Main Idea
The proposed method unites the advantages of the N-side filling method[4] and the surface interpolation method[5]. In a section where two surfaces are connected with $G^1$-continuity, the cross boundary derivatives are calculated based on the basis patch method used in the surface interpolation method to generate the control points. The control points in a surface are generated by approximating sample points by using the N-side filling method. The concept of our method is shown in Fig.1 (d). The blue markers show the control points calculated by the N-side filling method and the red markers show the ones calculated by the surface interpolation method. By unifying the control points obtained by the two methods, it becomes possible to generate surfaces that are $G^1$-continuous with adjacent surfaces of concave shape or with holes. Moreover, by using the sample point generation method independent of the number of $G^1$-continuous boundary edges, it is possible to generate a surface surrounded by surfaces in all directions connecting with $G^1$-continuity. Our surface fitting method proposed in this paper is executed in the following three steps:

**Step1:** Generating boundary curves that cover a closed region. As shown in Fig.2 (a), we consider surface fitting for a region $F$ that has adjacent $G^1$-continuous surfaces $F_2$ and $F_1$. If the boundary edges are $G^1$-continuous with the adjacent surfaces, sample points
are generated on the boundary edges and the edges are approximated by B-spline curves. If the boundary edges are not $G^1$-continuous with adjacent surfaces, the cross boundary derivatives are generated in the outside of the region, and the intersection points with reference planes that include a closed region are generated. Then, a set of the generated intersection points is approximated by a B-spline curve. After that, corner points of the four boundary curves are connected and a closed four-sided region is generated as shown in Fig.2 (a), enclosed with purple lines. The generated four-sided region is the boundary curves of a B-spline surface.

Step2: Generating sample points. In method[1], when the boundary edge is connected with the adjacent surface with $G^1$-continuity, the sample points are generated only on the boundary edge. Due to this, if the number of boundary edges connected with the adjacent surfaces with $G^1$-continuity increases, the number of sample points decreases and the control points of the B-spline surface calculated by the least-squares method are unstable. In our method, first, a B-spline surface that covers a closed region is generated by the N-side filling method. Then, as the purple markers of Fig.2 (a) show, the points on the generated surface existing inside the closed region are acquired as sample points. The sample points can be generated without depending on the number of boundary edges connected with adjacent surfaces with $G^1$-continuity.

Step3: Generating surfaces and control points connecting two surfaces. This section describes how to generate $G^1$-continuous surfaces. The cross vectors of the boundary edge of the two surfaces are calculated based on the surface interpolation method. As the red arrows of Fig.2 (b) show, knots are inserted in the parameters corresponding to the corner points of the boundary edges that connect the adjacent surfaces with $G^1$-continuity, and the boundary curves are divided. When the boundary edges connect adjacent surfaces with $G^1$-continuity in two adjoining directions, insert a knot near the corner[3] as the blue arrows of Fig.2 (b) show. This minimizes the section that is discontinuous with adjacent surfaces in a corner. After that, the cross vectors connected to each of the divided boundary curves are calculated based on the basis patch method and restrained control points are obtained.

Fig.2 (c) shows the result of our method applied to the closed region that has adjacent $G^1$-continuous surfaces in two directions, three directions and all directions.

Conclusions
In this paper, we proposed the reconstruction method of trimmed surfaces with maintaining $G^1$-continuity with adjacent surfaces. Our method is applicable to the shapes with holes or concave shapes. Moreover, our method is independent of the number of boundary edges that connect the adjacent surfaces with $G^1$-continuity, that is, our method is also applicable to a region surrounded by surfaces in all directions connecting with $G^1$-continuity.

References
Extended Abstract 27

Title
Extraction of surface-feature lines on meshes using normal tensor framework

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Keywords
Surface-feature line, Fillet edge, Normal tensor, Tensor smoothing

Introduction
Surface-feature lines are curves on surfaces, which are important for characterizing their shapes. They are lines which become $C^1$ boundary curves such as fillet edges and boundaries between convex and concave regions as well as sharp edges as $C^0$ boundaries. In geometry processing as mesh denoising or simplification, feature lines should be preserved and may become a part of segmentation boundaries. Various studies as [6] have proposed to extract the feature lines which correspond to ridges/valleys (also called crest lines) defined on a smooth surface as the locus of points where the maximum/minimum principal curvature takes a positive maximum/negative minimum along its curvature direction.

Crest line becomes useful in various applications, but it is insufficient for characterizing a shape in the industrial/mechanical objects as shown in Fig.1 (a). In those models, the high-curvature region is usually composed of smooth transition surface between two underlying surfaces, and the feature lines are the boundaries of this transition surface (called fillet) that should be extracted as shown in Fig. 1(b). Detecting the surface-feature lines, we get high-quality mesh segmentation in which each region should be divided by these lines as shown in Fig. 1(b) and Fig. 2.

The existing studies, using dihedral angle [2] or clustering method as [3], detect insufficient $C^1$ boundaries. They suffer from setting the threshold for distinguishing $C^1$ boundary vertices on which the dihedral angles are very small, because the angular value strongly depends on the mesh size, and the number of clusters affects the quality of results. In this study, we address the problem of extracting surface-feature lines from meshes even though they include noise.

(a) flat shading (b)Surface-feature lines
Fig. 1: Industrial/mechanical object

Main Idea
Normal voting tensor (simply normal tensor below) is a powerful tool for classifying feature saliences: surface, crease, and corner by the eigenvalues $\{\sigma_{120} \leq \sigma_{203} \leq 0\}$ of the tensor, and the corresponding eigenvectors $E_i$ ($i=1,2,3$) satisfy $E_i E_i = \delta_{ij}$ and $E_3$ is used to determine the ridge direction [4]. Although the crease and corner vertices are obtained as candidates for the points on a surface-feature line, foremost studies [2, 3] based on the framework fail to detect complete $C^1$ boundary vertices as mentioned above. Furthermore, in scanned data with large noise, the eigenvector $E_3$ does not indicate the ridge direction correctly. Therefore, we develop an algorithm for detecting surface-feature lines according to a change of curvature values instead of the angle values and enhance the normal tensor framework against noise.

First, we introduce a principal curvature equation in the normal tensor framework. Our method does not calculate second order derivatives which are very error-sensitive. Principal curvatures are given by eigenvalues of $3x3$ shape operator matrix: $S=\delta^T(\nabla N)\delta$ where $N$ is surface normal, $\delta$ is the projection operator defined by $I - \nabla N \nabla$ and $\nabla$ denotes the gradient. According to [1], $S$ is transformed into $2x2$ matrix $S'$ with any orthogonal basis $(T B)$ to $N$: $S' = (T B) (\nabla N) (T B)$. Here we notice that the orthogonal basis $(E_2 E_3)$ to the robust normal vector $E_1$ have already been known via the normal tensor. Hence, we can easily obtain the principal curvatures, $K_{max}$ and $K_{min}$, as the eigenvalues of Eqn. (1):

$$S' = (E_2 E_3) (\nabla E_1) (E_2 E_3). \tag{1}$$

Second, for noisy data, we perform an anisotropic smoothing of normal tensor itself [3] by the following Eqn. (2):

$$A_{n+1} = A_n + \alpha \sum_{j \neq n} \sum_{i \in \Omega} \omega_k (A_{j} - A_i), \tag{2}$$

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
Page 84 of 226
where $A^n$ is normal tensor at $V_i$ in the $n$-th step, $\lambda$ is a time-step variable and $w^\lambda_{ij}$ is an anisotropic weight. In Fig. 3, upper figures show the normal filtering effect due to the improvement of surface normal $E_1$, and lower ones visualize the direction $E_2$ and $E_3$ before/after smoothing. Then, we can obtain the appropriate principal curvatures from Eqn. (1) using eigenvectors of filtered normal tensor.

Once we have obtained the principal curvature $K_{\text{max}}$ and filtered principal directions $E_2, E_3$ for each vertex from noisy data, we can detect the surface-feature lines whose control points are interpolated by the vertices having the following properties: a vertex $V_i$ is the point if

1. the gap of $K_{\text{max}}$ exists in its principal direction $E_1$ in neighborhood of $V_i$. For example, the vertices on (A) yellow lines in Fig. 4(a) satisfy this condition;
2. the principal directions in non-flat regions differ (mutually orthogonal) as shown in (B) of Fig. 4(a) (b);
3. the sign of curvature changes in the direction $E_2$ as shown in (C) of Fig. 4(a).

(a) noisy data  (b) normal smoothing  (a) surface-feature lines  (b) $E_2$ (red) / $E_4$ (green)

Fig. 3: Anisotropic normal tensor smoothing.

Fig. 4: Surface-feature lines and principal directions.

(a) mean curvature map and enlarged detail  (b) surface-feature lines (our result)

Fig. 5: Result for scanned data of a car in the market.

Conclusions

Compared with the existing results shown in [2, 3], our method extracts the surface-feature lines as shown in (A), (B), and (C) of Fig. 2. Furthermore, owing to our anisotropic smoothing of normal tensor without vertex relocation, we could obtain the filtered surface normal and principal directions robustly and efficiently, and could estimate the principal curvatures. Then, we have extracted the lines as shown in Fig. 5(b). Consequently, our method can extract surface-feature lines without relying on critical values of dihedral angles [2] and vertex clustering [3].

References

Extended Abstract 28

Title
Interface adaptability for an industrial painting machine

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Keywords
Adaptable interface, Design for assembly/disassembly, Product design

Introduction
Adaptable product allows users to improve or change product functions by upgrading or replacing of functional modules of the product [3]. The product can therefore be functionally beyond its designed life cycle. Extending the life of a product provides a better sustainable solution than making a new product, as it reduces the resource consumption and waste generation associated with the new product and abandoned product. This research uses the adaptable concept to analyze interfaces of an industrial painting machine to improve machine’s sustainability.

The industrial painting machine is used in the toy industry to paint surfaces of toys made of plastic or metal materials. As shown in Fig.1, a feeding wheel delivers workpiece into the painting area, robotic manipulators are used to control areas for painting and cleaning in the operation. The completed piece is moved out of the machine for following processes. The machine uses two independent manipulators for surface painting and cleaning operations respectively. As a variety of painting colors, areas and processes is required by different toys’ types, sizes and shapes, the size of painting nozzles and motion of painting arms in the manipulator are variable. The current machine is designed as an integral system. The machine has to be redesigned for users if the painting parameter, such as toy’s size or shape, changes. The purpose of this research is to propose an adaptable painting machine to meet different requirements. It is to develop common platforms for a general purpose, and special function modules for the individual need. Interfaces have to be easily operated for adaptable requirements, especially, to allow users to make the module changes in their working place. The adaptable interface is therefore essential in the connection of modular elements for the product functionality. This paper investigates existing interfaces used in the machine to improve the machine adaptability. The interfaces are evaluated and improved based on measures proposed for the interface efficiency to meet the requirement of adaptable painting machines.

Main Idea
As adaptable products promise that the product function upgrading or changing can be performed by either product developers or users by adding or replacing functional modules of the product, the interface of adaptable products should be designed for easy operations of assembly and disassembly when the product modules are updated. This research focuses on mechanical interfaces as their complex in geometry and operation compared to power and information interfaces. The interface is represented using a connection graph to identify the way that components are linked [1]. Functional modules are decided based on the functional requirement and design parameters. The machine can be formed by eight modules with independent functions. Seven interfaces are identified as shown in Fig. 1.

Using the research solution of design for assembly and disassembly, evaluation criteria of the interface adaptability are proposed based on the geometrical and operational complex of the connection operation for modules and interfaces. The factors and data are collected based on the common measures used for the evaluation of product assembly and disassembly [2, 4]. The criteria used include connector attributes (e.g, number, size, weight, etc.), positioning attributes (e.g, ease of position, easy of handling, etc.), and operation attributes (e.g, accessibility, ease of assembly, tool applications, etc.). A measure of the interface efficacy (IE) is proposed as: \( IE = f (V_p, V_c, V_g, V_o, V_r, V_a) \), Where, \( V_p \) - Index value related to parts connected; \( V_c \) - Index value related to connectors used; \( V_g \) - Index value related to geometry complexity; \( V_o \) - Index value related to operation complexity; \( V_r \) - Index value related to tools used in the operation; \( V_a \) - Index value related to spatial accessibility. Geometry complexity includes parts’ size, shapes and weight, etc. Operation complexity considers the fastener operation and position. Index values are described using the coefficient, a number between 0 to 1. The values of these elements are assigned by weighting factors for their importance in the interface operation. Then, the weighted IE is formulated as: \( IE = (W_pV_p + W_cV_c + W_gV_g + W_oV_o + W_rV_r + W_aV_a) \times 100\% \), where \( W_p, W_c, W_g, W_o, W_r, W_a \) are weighting factors of items in the calculation equation, including parts connected,
connectors used, geometry complexity, operation complexity, tools used in the operation, and operation accessibility, respectively. In this research, these weighting factors are set as the value of 0.1, 0.2, 0.2, 0.1, 0.2, respectively, representing the importance of these evaluation aspects. The total of weighting factors equals 1.

Using the proposed IE, the existing interface efficiency is evaluated. The solution is analyzed to improve the interface design based on the criteria. The interface structures and connection methods are then revised to improve the IE. Tab. 1 shows the IE comparisons of interfaces before and after the improvement.

![interfaces in the painting machine](image)

**Tab. 1: Comparison of Interface improvement**

<table>
<thead>
<tr>
<th>Interface</th>
<th>IE (before)</th>
<th>IE (after)</th>
<th>Improvement</th>
</tr>
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<tr>
<td>1</td>
<td>72.6%</td>
<td>84.8%</td>
<td>12.2%</td>
</tr>
<tr>
<td>2</td>
<td>70.3%</td>
<td>86.7%</td>
<td>16.4%</td>
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<td>10.4%</td>
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<td>89.1%</td>
<td>17.0%</td>
</tr>
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<td>53.7%</td>
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<td>20.4%</td>
</tr>
<tr>
<td>7</td>
<td>53.7%</td>
<td>74.1%</td>
<td>20.4%</td>
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</table>

**Fig. 1: interfaces in the painting machine**

**Conclusions**
The interface plays an important role in the replacement of functional modules for product adaptability. This research suggested a measure of the interface efficiency. The measure provides a direction to improve the design of interfaces for the adaptable painting machine. An initial test shows the improvement of the operation with the reduced time and efforts to change functional modules for different requirements. Further work will analyze the entire structure of the machine from top to bottom using the adaptable design method to improve adaptability of the machine.

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**References**
Extended Abstract 29

Title
Managing equivalent representations of design and analysis models

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Keywords
CAD-CAE integration, Cellular Modeling, Virtual Topology, Equivalencing

Introduction
Pressure to continuously design cost effective, superior products in less time has resulted in the use of computational engineering analysis throughout product development cycles. An effective design process requires seamless integration between CAD and CAE tools, with design decisions based on analysis results driving the design process, and many analysis iterations being utilized to provide optimal design decisions. One fundamental issue regarding seamless CAD – CAE integration is the difference between design and analysis geometries, with fully featured manufacturing detailed CAD models used for design and abstracted versions of the design model required for different types of analysis. Industry uses specialist functionality from many commercial packages, resulting in simulation models with no robust link between them.

Thakur [6] details the multiple research efforts focusing on automated CAD model simplification tools to generate the desired abstract analysis geometry, but they do not create the necessary associativity between the different representations. Several attempts have been made to achieve such integration, where the design model is automatically linked to various analysis models. Lee and Lee [2] describe the use of a single non-manifold master model to store all features along with their appropriate idealizations. Shephard [5] describes a simulation model manager to construct analysis models, without actually linking the models. These approaches do not provide a generic solution able to deal with B-Rep geometry at any stage of a CAD-centric or CAE-centric design process, whilst still providing the bidirectional associativity necessary for successful design and analysis integration. The approach detailed here addresses these problems by managing all equivalent representations required for different analyses and between different packages.

Main Idea
In this work it is demonstrated how three core technologies named Cellular Modeling, Virtual Topology and Equivalencing can be used to manage and manipulate the topology of geometric design and analysis models in a coherent, integrated fashion, independent of any underlying CAD or CAE system.

Here the concept of Cellular Modeling [1] is expanded upon, with the cellular model being considered at its lowest cellular level, allowing links to be made to all other representations of the same model. However, the non-manifold cellular model used in this work contains multiple cells representing the entire design space, including both solid and fluid domains, Fig. 1 (a), cells to which different analysis attributes (e.g. meshing styles) could be applied, or for defeaturing purposes cells could represent features essential for design but superfluous for all but the most detailed analysis. Each cell in this decomposed cellular model, Fig. 1 (b), can be utilized for different analysis types, with attributes being used to define their parent entity and simulation significance. Cells may be used for different applications in different analyses, for example it may be that cells are considered solid for one stage of the design, but may be represented as 0D masses and inertias in another analysis.

Figure 1: Cellular models: (a) Original, with solid (dark) and fluid (light) cells, (b) Decomposed, (c) Idealized.

In this work a separate data structure is used to store the topological connectivity information (vertices, edges, faces and bodies) of the non-manifold cellular decomposition, Fig. 1 (b) [3]. The non-manifold topology in the database is linked to its...
equivalent manifold topology in the CAD/CAE environment allowing commercial packages without non-manifold capabilities to avail of this approach. Sheffer [4] introduced the concept of Virtual Topology as a model simplification tool without the need for direct geometry editing. Some CAE packages use virtual topology internally without informing the user. In this work, virtual topology is recorded in an open and transparent way, allowing it to be used by the analyst from any CAE environment.

Storing topology at its lowest cellular level enables fit for purpose analysis models to be derived using virtual topology, equivalencing and calculated interface information. Virtual topology is used to create new cellular representations using subsets and supersets of the existing decomposition. Virtual subsets can be created to partition an existing model so that appropriate analysis attributes can be applied. A virtual superset of existing cells can be created in the data structure, with the decomposed solid cells stored as subsets to remove any unnecessary partitions. In this manner the topology of original un-decomposed cells is created using pre-built SQL queries to calculate common boundaries between subset entities and identify the correct lower bounding topology to be merged. Idealized models can also be managed, Fig. 1 (c), where thin-sheet and long-sleender regions [3] are represented by appropriate mid-surface and beam idealizations respectively. Equivalencing information stored in the database keeps track of dimensionally reduced idealizations (face collapsed to an edge etc.). This allows analysis models of different fidelity to be automatically generated. One important feature of this approach is to maintain the relationship between the topology in the database and its 3D representation. Geometric inaccuracies between systems are accounted for by applying tolerances within the data structure, which allows all topological entities to be persistently named between packages with varying data structures.

![Figure 1: Mesh geometry associativity: (a) Efficient mesh on decomposed model, (b) Original design geometry, (c) Orphan mesh, (d) Efficient mesh fully associated with original geometry.](image)

This method allows multiple different packages to be utilized for a single design process giving access to their specialist technology with all models completely linked. One tool is used to decompose design geometry for meshing, another is used to apply efficient meshing strategies to the decomposed cells based upon their geometric properties, Fig. 2 (a) and based upon analysis requirements other packages are selected for their solving capability. Here the mesh is fully associated with the original geometry, Fig. 2 (d). After design changes or topology updates during optimization, these associations can be used to identify subsets of the design model at a local instead of global level for remeshing or abstraction, or for transferring results across domains for multi-disciplinary analysis.

Conclusions
A flexible data structure and automated tools have been developed allowing multiple CAD and CAE tools (e.g. Parasolid, NX, Abaqus and CADFix) to interact with one another so that analysis models and attributes can be transferred between packages without any loss of integrity. Analysis attributes can also be transferred between models of varying fidelity, where adjacencies in lower fidelity models are derived through equivalent relationships in the cellular model.

References
Extended Abstract 31

Title
Curvature-Continuous Approximation of Planar Curvilinear Profiles

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Keywords:
Cubic B-Spline, Approximation, G2-Continuity, Tolerance Zone, Voronoi Diagram

Introduction
Smooth approximations of planar curvilinear profiles that consist of straight-line segments and circular arcs are useful both from a theoretical and a practical point of view. The general goal is to represent one or more open or closed profiles by a comparatively small number of higher-order primitives within a user-specified tolerance, which might be asymmetric or even one-sided, thereby achieving curvature continuity (G2). Applications like the simplification of geographic entities (such as islands within a lake or river) in a geographic information system also require us to maintain the topology of the input. That is, the approximation curves generated are not allowed to self-intersect or to intersect each other. Actually, in VLSI applications we may even be asked to guarantee a minimum clearance among the approximation curves in order to prevent undesired connectivity.

However, we are not aware of algorithms that allow the simultaneous approximation of a set of planar profiles by G2 curves such that both the approximation tolerance is controlled and the input topology is preserved. The work by Heimlich and Held [3] allows to control the approximation tolerance and preserves the input topology, but it achieves only a G1-continuous approximation by based on biarcs and it is restricted to sets of closed polygons. Here we sketch an extension of their work to multiple open or closed profiles that do not intersect, and describe how a G2-continuous approximation is achieved if the profiles consist of straight-line segments and circular arcs.

Main Idea
As in [3], we make extensive use of the Voronoi diagram of the input profiles. Roughly, the Voronoi diagram of straight-line segments and circular arcs as input sites partitions the plane into regions such that every region corresponds to a site and such that it consists of all points closer to that site than to any other site. From the Voronoi diagram the medial axis is obtained easily since it forms a subset of the Voronoi diagram. (See [1] for a formal definition and detailed discussion of Voronoi diagram and medial axis of segments and circular arcs.)

The algorithmic vehicle for guaranteeing a user-specified maximum (Hausdorff) distance between the input profiles and the approximation curves, for achieving the simplicity of the approximation curves, and for maintaining the input topology is the use of a tolerance zone, see Fig. 1: Every profile (and its approximation curve) is contained in its own portion of the tolerance zone whose width is chosen such that the bound on the Hausdorff distance is obeyed. To this goal we extend the definition of a tolerance band in [3] to open curves. To compute the boundary of the tolerance zone, we use traditional (Voronoi-based) offsetting and add pseudo offsets and spikes as described in [3]. The resulting boundary is approximated by straight-line segments in order to facilitate subsequent intersection tests.

We use uniform cubic B-splines as approximation primitives to achieve G2 continuity. These spline segments are defined upon four control vertices each. We apply an appropriate simplification of de Boor's algorithm, taking the uniform knot sequence into account to conduct fast intersection tests. These intersection tests check whether the approximation leaves the boundary of the tolerance zone and, thus, determine whether an approximation primitive is valid. The B-spline primitives use so-called approximation nodes ("a-nodes") as control vertices. These a-nodes are generated within the tolerance zone and placed on its medial axis.

Since consecutive B-spline segments share a common set of control vertices rather than only one a-node, standard greedy-like schemes [3,4] for fitting "long" primitives to the input cannot be adapted easily to B-splines. To overcome this problem we developed a top-down approach that refines an initially coarse approximation in a divide&conquer style: We start with one coarse primitive and refine it by subsequently adding new approximation nodes if the primitive is not contained entirely in the tolerance zone, thus splitting the coarse primitive into two smaller ones. We stop when all primitives lie within the tolerance zone. The a-nodes are generated during the computation of the tolerance zone, and every a-node has pointers to the tolerance zone boundary. Thus, tests for containment of a primitive in the tolerance zone are handled by determining an appropriate set of boundary segments which are individually checked using de Boor's algorithm.

International CAD Conference and Exhibition, Final Program CAD'13 Volume 10  Page 90 of 226
The polynomial form of uniform cubic B-splines in power basis implies that the resulting curve is incident in a specific point if three control vertices coincide at this position. Thus, we add these points as control vertices three times each to approximate open curves with fixed start and end point. This approach can be applied to both open and closed profiles. To support closed profiles we use a circular iterator on the resulting list of control vertices.

(a)  
(b)  
(c)  
(d)  
(e)  
(f)  

Fig. 1: The top row shows from left to right (a) the input letter “a”, (b) its Voronoi diagram (in green), (c) the tolerance zone with blue right boundary and magenta left boundary, and (d) the a-nodes and the final approximation in orange. The bottom row shows the approximation of (e) an open polygonal curve and (f) of a rectilinear polygon. (For the sake of visual clarity we used unusually large approximation tolerances.)

Discussion

We implemented our algorithm in C++, based on the Voronoi package “VRONI” [2]. Extensive experiments with synthetic and real-world data sets show that it works nicely in practice. Due to the use of Voronoi-based computations, our approximation algorithm is completely immune to input noise: As the approximation tolerance is gradually increased, the number of B-spline primitives used decreases gradually. Our top-down approach yields a smaller number of B-spline primitives than the standard greedy-like fitting schemes. It is also significantly faster, running in less than ten seconds on a standard PC for up to 10,000 input segments and arcs. From a theoretical point of view, the overall algorithm runs in \(O(n \log n)\) time and requires \(O(n)\) space: The Voronoi diagram of \(n\) segments and arcs can be computed in \(O(n \log n)\) time [1], and the computation of the tolerance zone requires \(O(n)\) time. For every recursive refinement an intersection check is conducted and a constant number of a-nodes is added. This intersection check with the boundary of the tolerance zone can require at most a linear number of intersection tests against straight line segments. Hence, the actual approximation algorithm also runs in \(O(n)\) time.

References


Extended Abstract 32

Title
A Decision Support System for Analog Circuit Design using Genetic Algorithms

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Keywords
Analog circuit design, Design automation, Genetic Algorithms, Graph Theory

Introduction
Over the last three decades researchers have been investigating extensively, e.g. [2-5] the design, control, and planning of analog circuit design. The aim is to create a circuit diagram that satisfies the specified design goals and obeys the drawing rules globally known as IEC standards. Both the topology and the sizing must be chosen such that the resulting circuit satisfies the design objectives. Aaserud and Nielsen [1] noted the following: “In contrast to digital design, most of the analog circuits are still handcrafted by the experts and so-called “zahs” of analog design. The design process is characterized by a combination of experience and intuition and requires a thorough knowledge of the process characteristics and the detailed specifications of the actual product. Analog circuit design is a knowledge-intensive, multiphase, iterative task, which usually stretches over a significant period of time and is performed by designers with a large portfolio of skills. It is therefore considered by many to be a form of art rather than science”.

This paper presents a Decision Support System (DSS) to automate circuit design and enables several degrees of interactive design. The work is based on two main stages, first using Genetic Algorithms to map the topology of the relevant devices, and secondly, a Graph theoretic approach for connecting the devices in a restricted manner to provide explicit criteria.

Main Idea
Our solution process is done by solving two sub-problems. First the placements of the devices which will be done using Genetic algorithms (GA’s), which are powerful, search techniques that are used successfully to solve problems in many different disciplines. It is then followed by the second sub process which combines routing preferences by using Search algorithm, A*. A two layered Altruism over the solution of A* search will be implemented to provide a better rank for the criteria formulated in the fitness function. GA’s.

As we develop a DSS, the input is the following dataset: \( U(\text{designation}, P_u \subseteq P) \) A set of units; \( P \) \( \{ \text{designations}, S_i \in S \} \) – A set of pins; \( S \) \( \{ \text{designation} \} \) – A set of signals. The Fitness Function is composed of the following criteria: Number of Lines Exceeding \([\text{min, max}]\) Range Line lengths, \([\text{Standard Deviation}], \) Number of Line intersections and Number of Connected pins miss-aligned. An example of the chromosome is depicted in Figure 1.

![Fig. 1: A chromosome of the population containing the placement and the orientation.](image)

Our routing algorithm is built over two layers. The first is a generic path-finder using A* which can efficiently find a good path connection, taking in consideration the limitations such as unreachable positions, turns, intersections and lengths. The second includes aspects of altruism, where a connection that is well defined and satisfies optimal criteria, gives up his position to provide a better routing preference to another device, aiming at a better overall solution, see Figure 2 that depicts the procedure.

Figures 3-4 depict the DSS alternative configuration constraints and an example of an automatic layout design of a circuit.

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
Conclusions
This work presents a process of circuit layout design by combining GA fitness parameters, A* search and altruism, layered in a multiphase manner which mimics the intelligence required by experts.

References
Extended Abstract 33

Title
Voxel-based path planning for optimal 3D scanning of mechanical parts

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Keywords
Scanning path, visibility, Voxel-map, digitizing system

Introduction
Within the context of 3D surface scanning, path planning is still a challenge to obtain a complete representation of parts in a minimum time. More generally, path planning is defined as a set of ordered points of view allowing the part digitizing without collision. Each point of view corresponds to one sensor configuration relatively to the part and allows the digitizing of one portion of the part surface. As the common objective is to minimize cycle time, the main difficulty linked to scan path planning is to define a sensor trajectory, free from collision, that leads to a good surface representation, i.e. slightly noisy and complete. This issue can be expressed as the minimization of the number of points of view while respecting quality criteria, and avoiding collisions and occlusions. This issue has been widely addressed in the literature for parts defined by a CAD model. Most of the methods adopt the part standpoint through the concept of part visibility: what are the directions from which a point of the part surface is visible? Visibility calculation of a point is based on the knowledge of the local normal at the point. Starting from the CAD model, Xi and Shu determined optimal digitizing parameters so that the digitized surface is maximized. They split the surface into sections, each one defining a surface portion. For each section, the optimal positioning is obtained by aligning the field of view with the projected surface frontier [1]. Son et al. proposed a method for path planning dedicated to a laser-plane sensor mounted on a CMM. The CAD model is sampled into points and corresponding normals, with the objective of finding the minimum number of sensor configurations. The sampling is constrained by the size of the laser beam so that the distance between two consecutive points is less than the beam width. These two consecutive points can be digitized with the same sensor configuration if the angle between the normals is less than twice the view angle of the sensor [2]. Martins et al. proposed a voxel-based approach. The CAD model is reduced into a coarse voxel-map allowing the calculation of the local normals, and defining the space volume to calculate collision free trajectory. In function of the point of view accessibility, voxel can be classified as Surface, Empty or Inside [3]. Starting from a surfel, Rafaelli et al. gathered areas in function of the normal orientation. Each area is afterwards represented as a Nurbs surface[4]. Most of the literature methods are generally well adapted for a given sensor. The method proposed in the paper is generic and suitable for any type of sensor. The approach adopts the sensor standpoint starting from the minimum number of points of view that can be defined in relation with the sensor field of view and the part dimensions. This leads to the part modeling as a voxel-map wherein the voxel size is given by the sensor field of view. The analysis thus consists in finding portion of the surface visible by the sensor point of view. A quality criterion is also added to the notion of surface visibility.

Main Section
As scan path planning aims at minimizing the number of points of view leading to the complete part digitizing, the originality of the proposed approach lies in initializing the search process by considering the minimal number of points of view allowing the entire digitizing of the part volume bounding. This minimal number of points of view is defined in relation with the size of the sensor field of view and the part dimensions (see Fig. 1(a)). Orientations are first selected along the X, Y, Z-axes of the space. This initial set of viewpoints is equivalent to the part modeling as a voxel-map for which the voxel size (L) is equal to the size of the sensor field of view. The next step is the visibility analysis. The voxel $k_1$ of the voxel-map is visible from the point of view $p_1$ and it is also visible from $q_{out}$ if it is not visible from the point of view $p_{1+1}$ (Fig. 1(b)). Therefore, it is possible to determine for each point of view, the set of visible voxels. At this stage, a consistency analysis is performed to ensure that the voxel is a good representation of the surface portion included. Actually, the surface portion included in the voxel may present local curvature variations (Fig.1(c)), that means local normal variations not consistent with the visibility associated with the point of view. Therefore, we propose to assess the voxel normal consistency with regard to the surface portion. The voxel normal is defined as the mean value of the normal to the facets defining the surface portion included into the voxel (Fig. 1(b)). If the consistency is not assessed, the voxel
subdivision is carried-out until the consistency criterion is reached. This subdivision involves the addition of points of view to the initial set. However, as the subdivision is not systematic, the benefit in computational time is significant. The last step consists in the quality analysis. Indeed, some studies showed that if the angle between the digitizing direction and the normal to the surface is important (classically around 60° for laser-plane sensor), the digitizing noise as well as the trueness can be affected leading to a low quality of the digitized points [5]. In this direction, the point of view is assessed or not thanks to quality criteria. This leads to define new orientations in relation with the normal and the quality. Once, all the points of view are determined, the sensor trajectory can be defined by joining the points by straight lines following a zig-zag strategy.

This method has been applied to a complex part, with two different types of sensor in order to assess its efficiency, the first one with a 250 mm FOV size and the second one with a 50 mm FOV size. For each case, the set of points of view (in blue) is displayed in Fig. 2. The initial voxel-map is represented in green, while normals are represented in red. Whatever the sensor, the method provides a set of admissible points of view to ensure the complete surface digitizing.

Fig. 2: Sets of points of view for two different sensors.

Conclusions
An original method to determine optimal scanning path is proposed based on the size of the sensor field of view. Starting from the minimal set of points of view admissible with regard to the field of view and the part dimensions, the algorithm checks the validity of the points of view in terms of visibility of the surface and digitizing quality. The visibility analysis relies on an adaptive voxel-map of the surface which limits significantly computational time. As illustrated through two different digitizing systems, the method applies for any type of sensors leading to the set of points of view allowing the complete part digitizing. The scan trajectory is afterwards defined accounting for occlusions. This step will be described in the final paper.

References
Extended Abstract 36

Title
Feature-preserving outermost-surface polygonization from CT images

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Keywords
isosurface extraction, outermost surfaces, void structure, morphology

Introduction
This paper presents a simple method for computing high-resolution outermost-surfaces from CT images. The concept involves identifying internal structures known as voids from such images. To detect these structures, a closing operator is applied in mathematical morphology [3] to binarized images, the CT values of the void region are then replaced with sufficiently large values, and common polygonization methods (such as Marching cubes algorithm[2]) are finally applied to the modified CT images. As the CT values of void structures are modified, these regions are not polygonized.

The main advantage of the method is its capacity to simplify the topological structure of isosurfaces. As polygonization using the Marching cubes algorithm is faithful in terms of image CT values, the results often include complex parts due to the structure of voids in the target object. This is prevented with the proposed method because it involves manipulating the CT values of these regions, which also helps to reduce the number of faces. In addition, the method calls on the use of the Marching cubes algorithm for polygonization and inherits several advantages, such as sub-voxel accuracy and intuitive parameter tuning. Moreover, the method is simple and easy to implement with GPGPU. Indeed, prototype implementation in this study resulted in a level of performance several times faster than CPU-based application.

Main Idea
The objective here is to compute simply structured polygonal meshes and surface feature details from CT images. Given such images of the target object (Fig. 1 (a)), the proposed algorithm can be used to compute surfaces via the three simple procedures of void detection from binary images (Figs. 1 (b), (c)), CT value manipulation (Fig. 1 (d)) and polygonization based on the Marching cubes algorithm (Fig. 1 (e)). The resulting surface is simple because complex structures are filled. With this method, the user specifies the two parameters of \( t \) (the polygonization threshold) and \( r \) (the radius of the sphere or structural element).

![Fig. 1 An overview of our method in 2D. (a) Input image. (b) Binary image. (c) Detection of void image. (d) Manipulation of CT value. (e) Isosurface extraction result from (d)green.](image)

Results
Fig. 2 shows several results our method for fossil skulls (Amud 1) and Skull model. From left to right, the input CT images, our computation result, isosurface from the CT images are shown. In addition, the right most images shows internal structure of the object in red. We confirmed that our method could remove this structure by our method although surface quality is preserved. Indeed, the numbers of faces of Amud 1 and Skull data are 85 and 60 \% of original faces, respectively. The results can be used for surface inspection, reverse engineering and medical applications [1].

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
Fig. 3: Results. From left to right: Input CT images, Our results, Marching cubes result for the original images and detected void structure (red).

References
Extended Abstract 37

Title
Simulating a System of Locomotion Similar to the Architecture of the Frog via Oblique Planes.

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Keywords
Frog, Parabolic trajectory, Parametric design, Locomotion, Prototype.

Introduction
Today, researchers at several universities are working on the imitation of the operation of biological organisms inspired in animals through mathematical models, at the laboratory of the university we are working the same subject but through descriptive geometry, i.e. we represent the planes in space, and we focus on locomotion taking into account two important aspects: joints and movements of the oblique planes because:

- In the locomotion system, joints have the function to give mobility and stability to the parts of the structure.
- And in the locomotion system, the oblique planes keep their angular position when moving upward or downward, rightward or leftward and forward or backward.

This project starts from the premise of creating a system of locomotion similar to the architecture of the frogs, using the elements and resources of descriptive geometry, to identify, develop, describe and generate the morphological and functional behavior of amphibians, using the following methodology [5]:

- Development of the geometric and structural representation of the model.
- Generation of parametric design.
- Description of the movements (locomotion).
- Build the prototype.

In this paper we present the first part of the research on where they can analyze the structure and locomotion of the front legs of the frog design, contributing to the solution of geometric structures which simulates the movements of the amphibians with the handling of the oblique planes without losing sight of the concepts of physics.

Main Idea
The goal of this paper is to present the use of oblique planes in the construction and simulation of a system of locomotion similar to the architecture of the frog. To reach the goal of the research, in this study considers the anatomy and the skeletal structure of the frog (Fig. 1 a, b), resulting in the movement, and also the studies conducted by scientists from Brown University in Rhode Island in USA [1]. The process that was undertaken in this research is the following: it was performed a virtual model in the 3D Autodesk Maya program, to analyze the frog jump; in the Autocad program was traced the orthogonal projection in two and three dimensions to create the model (Fig. 1c), in the Inventor program were generated the parametric modeling, the assemblies, and the simulations, and performed the prototype with the 3D printer.

![Fig. 1: The frog, (a) Morphology [5], (b) Skeleton, (c) Model.](image)

To analyze and describe the locomotion of the frog in three movements before jumping: when the frog is at rest, when the frog is raised 21° and when the frog reaches 42°, it was necessary build three models in cardboard, (Fig. 2), to locate the points and lines containing the oblique planes and also to observe the movements of each of the oblique planes of the front legs of the frog.
As we can see in the figure #2, the front legs are formed by three oblique planes of four sides. An oblique plane is defined as a plane that is not at right angles with respect to another plane, which is inclined with respect to the three reference planes of the orthogonal projection and they are not in true form and magnitude.

In each of the oblique planes the triangulation is used to perform the movements of the frog, i.e. the edge takes the place of a hinge. If an oblique plane is greater than three sides is required triangulation. In geometry, triangulation is used to determine the inclination of the planes with respect to an edge, that is, the oblique plane is divided into triangles, each of the triangles are rotated either downward or upward to form the figure.

As shown in Figure 2, to simulate the mechanism of our model, a force is applied in the horizontal plane, so that when the plane is rotating in the direction of clockwise reaches the angle of inclination of 42° and the oblique planes keep their angular position, and when the horizontal plane is rotating in the direction of counterclockwise, all the planes returns to its original position.

The fundamental principles of the parametric design are the creation, positioning and adjustment of the components of an assembly and the simulation of mechanisms. In the simulation it was observed that when the horizontal plane, i.e. the body rotates, the oblique planes of the front legs of the frog rotate properly backwards and forwards and moves up and down, because the hinges were placed in different positions in space with respect to the axes x, y, z.

Once finished with the model analysis, the last step that was performed was to print the prototype (Fig. 4), generated with CAM applications, where we can see how the mechanism works.

Conclusions

This paper presents the simulation of a system of locomotion via oblique planes. From the triangulation of oblique planes, the front legs of the frog they moved simultaneously when it rotated upward and downwards the horizontal plane, i.e. the body of the frog, since each of the parties of the front legs of the frog, besides moving up and down, also rotates about the axis of the cylinders to the right and the left.

The results show that the design process that was carried out in this project, contributes to the solution of geometric structures to simulate the movements of the animals with the handling of the oblique planes without losing sight of the concepts of physics.

References

Extended Abstract 38

Title
The importance of Geometric Trace in the Accuracy of Digital and Physical Models

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Keywords
Geometry, axes, centers, Precision, Modeling

Introduction
When we design an object, we’re always seeking perfection in our models. Unfortunately there’s no machine or process with 100% precision. Several researchers in the materials and processes area explained to us that in order to make an almost perfect model we have to consider the geometric principles and proportion knowledge. The purpose of this investigation is to compare the accuracy between two prototypes of an hourglass of wood and plaster, as well as the human and technological precision. We considered the peanut’s morphology, a proportion ratio of 6, 3D modeling and scantlings. The models were made by the authors at the Universidad Autónoma Metropolitana, Cuajimalpa, in Mexico City. The two cases previously mentioned followed the methodology below:

- Sketching.
  - Two-dimensional geometric trace.
- Three-dimensional modeling.
  - Hourglass’ exterior.
  - Hourglass’ inside.
- Wooden model elaboration.
- Plaster model elaboration with 3D printer.
- Results.
- References.

Main Idea

Sketching: Before solving the figure in CAD Applications, we drew sketches of the hourglass. A sketch is a fast drawing by hand that shows the general characteristics of the model. It’s a way to have a first approximation of the object.

Two dimensional geometric trace: The profile’s stroke is the external shape of the hourglass. It was drawn by using a grid. First, we defined the grid’s height and width. The height was divided in a proportion ratio of 6. Then we delineate the profile using the Spline Fit tool. The intersections between the grid and the proportion ratio functioned as guide points to draw the profile. For the thickness, we made an Offset to the initial stroke. We realized that the curve exceeded the grid’s upper and lower limits leaving an open curve, due to the Spline Fit’s behavior. The problem was solved as follows:

Case A: The curve exceeding the grid was cut off using the tool Trim. Then the curve was joined with a straight line.

Afterwards, the Offset was performed without any trouble.

Case B: From the beginning, the Spline was generated from two horizontal lines corresponding to the flat bases. The trace was continued with the original methodology to generate the hourglass’ thickness.

Hourglass’ exterior: To obtain a solid hourglass, we revolved the stroke’s profile 360°. We had to join all the lines and curves into one single Polyline. The Splines were turned into 3D polylines using the command Pedit and a precision of 10. The 3D polylines were transformed into lines with the command Explode. At last, all the lines were joined using the command Pedit Join. Finally we copy and paste the hourglass’ profile to the center of the space adding a vertical axis.

Hourglass’ inside: The funnel’s shape is a conection of surfaces between 2 cones and a cylinder. We created a new grid from the middle 2/6 of the original proportion of 6. 4 circles were drawn corresponding to the cone’s upper and lower mouth, and the cylinder’s. The cone’s circles had the same length of the 2nd line of the proportion of 6. The cylinder’s bases radius measured the intersection between the thickness and the middle of the funnel’s grid height.

For the funnel’s thickness, we made an Offset of 1 cm for each circle according with the 3D printer conditions.
Using the Loft tool, the outer circles were joined, starting from the cylinder’s circles and then the cones’ circles. The same process was applied for the inner circles. To turn it into a solid, the cone’s outer surfaces were patched. From the axis, a new circle (measuring the same as the cone’s mouth offset) was drawn from above. It was projected with the Project Geometry command to perforate the patches from the upper view. Finally, with the Sculpt tool, all surfaces were selected and turned into a solid. After this, we realized that the funnel was intersected with the thickness of the hourglass’ surface, because the cone’s mouth was traced on the edge.

Case A: when the funnel was scaled, it losted the required thickness for printing and continued intersecting the hourglass’ surface. Because of this, the width of funnel’s mouths were decreased, ie give a tolerance to the edge. The drawback is that with the tolerance, the sand would leak from the sides, so it will need to be fixed with a sealant.

Case B: From the beginning, the hourglass’ width and thickness, didn’t allow to create a funnel.

Wooden model elaboration: The prototypes were produced using a wood lathe. A lathe is a mechanical tool which spins wooden block while a cutting tool gives shape. The length and shape of the cut are determined by the pressure applied to the material and its resistance. For its manufacturing, the CAD models, were scaled by 75% (case A) and 50% (case B) because of the lathe’s and model’s size and also the wood’s resistance. Each turner received an scantling and additionally in case A, the blueprints.

Plaster model elaboration with 3D printer: For the plaster prototypes the two models, these were scaled to the 50%, due to the dimensions of the 3D printer (200 x 200 x 250mm). The files were saved on an STL format, for the program Zprint.

Results.
Using the scantling, the measurements of each hourglass were compared (Tab. 1, 2)

<table>
<thead>
<tr>
<th></th>
<th>AutoCAD trace wooden/plaster</th>
<th>Wooden model</th>
<th>Plaster model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper base</td>
<td>60 mm/40 mm</td>
<td>43 mm</td>
<td>39.9 mm</td>
</tr>
<tr>
<td>Lower base</td>
<td>60 mm/40 mm</td>
<td>47.5 mm</td>
<td>39.9 mm</td>
</tr>
<tr>
<td>Maximum upper width</td>
<td>150.25 mm/100mm</td>
<td>135 mm</td>
<td>109.9 mm</td>
</tr>
<tr>
<td>Maximum lower width</td>
<td>150.25 mm/100mm</td>
<td>137 mm</td>
<td>109.9 mm</td>
</tr>
<tr>
<td>Minimum width</td>
<td>60 mm/40 mm</td>
<td>27 mm</td>
<td>29.9mm</td>
</tr>
<tr>
<td>Total height</td>
<td>375 mm/250mm</td>
<td>370 mm</td>
<td>249.9 mm</td>
</tr>
</tbody>
</table>

Tab 1. Case A.

<table>
<thead>
<tr>
<th></th>
<th>AutoCAD trace</th>
<th>Wooden model</th>
<th>Plaster model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper base</td>
<td>40 mm</td>
<td>42 mm</td>
<td>39.9 mm</td>
</tr>
<tr>
<td>Lower base</td>
<td>40 mm</td>
<td>41 mm</td>
<td>39.9 mm</td>
</tr>
<tr>
<td>Maximum upper width</td>
<td>80 mm</td>
<td>93 mm</td>
<td>79.9 mm</td>
</tr>
<tr>
<td>Maximum lower width</td>
<td>80 mm</td>
<td>95 mm</td>
<td>79.9 mm</td>
</tr>
<tr>
<td>Minimum width</td>
<td>15 mm</td>
<td>15 mm</td>
<td>14.9 mm</td>
</tr>
<tr>
<td>Total height</td>
<td>200 mm</td>
<td>198 mm</td>
<td>199.9 mm</td>
</tr>
</tbody>
</table>

Tab 2. Case B.

In both cases, the accuracy of the wooden model is 92.75% compared to the original traces. The plaster model had a 99.75% of accuracy, therefore, we can say that the pieces are almost perfect but they don’t have their real size. There is no process, either mechanical or handmade, that allows us to obtain a 100% precision.
Fig. 1: Scanntlings check (a) Case A, wooden model (b) Case B, wooden model (c) (d) Case A, plaster model (e) (f) Case B, plaster model.

References
Extended Abstract 39

Title
Slice generation and data retrieval algorithm for rapid manufacturing of heterogeneous objects

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Keywords
Rapid manufacturing, heterogeneous object, slicing

Introduction
Rapid manufacturing (RM) produces parts layer by layer using 3D CAD data generated during geometric modeling. The process planning tasks for layered manufacturing include orientation determination, support structure determination, slicing and deposition path planning. The layers are generated during slicing by mapping geometric information from 3D computer aided model to 2D layers with constant or variable thickness. Rapid manufacturing of heterogeneous objects (HO) requires additional information of material distribution at every point in the object domain. The few RM methods e.g. Stereolithography, Laminated Object Manufacturing, Selective Laser Sintering, Fused Deposition Modeling, and Inkjet Printing are capable of producing heterogeneous objects. The quality of fabricated objects is based on the accuracy and compactness of 2D data generated during slicing. The quality of data varies with different methods adopted for slicing. So, selection or development of slicing algorithm plays an important role in producing required quality heterogeneous objects. Various issues related to error in slicing contours have been investigated [1, 3-4]. Adaptive slicing method for reducing minimum fabrication time is developed [5]. The issues for improving geometric accuracy are discussed [2] and slicing algorithm was proposed to overcome computer memory constraints and computational problems. An idle slicing method should provide the accurate geometric and precise material composition at every point in each region of the HO slice. Slicing errors should also be reduced to minimum for better surface finish. The method should also offer local control at critical locations in the object to achieve significant functional requirements.

In view of above discussion, a mesh generated algorithm is proposed for scanning a layer for retrieving geometric and material information at each point in the layer domain. Slice thickness is varied for different contours and approximated to reduce the error between contours and the effect of geometry and material stair-step. A database system is developed for faster processing of information and to avoid the data redundancy during operation. The proposed algorithm and adaptive thickness method are implemented and some cases are discussed to show the validity of the work.

Main body
The information processing for slicing of heterogeneous objects for RM set up follows three steps; Pre-processing, Processing and Post processing.

Pre-processing is a set up task in which three parameters i.e. slicing plane, slicing direction and slice thickness are defined to slice the 3D CAD model of homogeneous/heterogeneous object. Any plane surface of HO can be selected as a slicing plane or user can also define own slicing plane i.e. the XY, YZ, ZX plane or a specific plane defined with three points. The direction of slicing, also termed as Z direction or build up direction, is defined along the normal to the slicing plane. Third parameter i.e. slicing thickness has required a lot of attention to minimize the stair-step effect i.e. geometric as well as material. An adaptive slicing algorithm is used to determine the layer thicknesses based on geometric and material distribution information in a 2D layer domain. The geometry-based layer thickness is computed based on the area variation rate between two adjacent slices. The material based layer thickness is computed by the gradient of material distribution and material resolution for each material. Both geometric and material based layer thicknesses are compared and minimum value is selected as slice thickness for the layer.

An example is demonstrated to find out layer thickness for a heterogeneous object as shown in Fig. 1. The object is sliced using uniform and adaptive slice method and methods are compared in terms of number of slices. In the implemented adaptive slice method, two thicknesses for each layer are computed considering geometric and material stair-step effects as shown in Fig. 1(c) and 1(d) respectively. The minimum of two is selected for slicing the heterogeneous object as shown in Fig. 1(e).

Processing step basically generates the slice for rapid manufacturing of heterogeneous object and is completed in two steps; Contour generation and Mesh generation and material mapping. In rapid manufacturing, the slice at a prescribed height is obtained by slicing the object with a horizontal plane at that height. The horizontal contour of the slice is determined exactly from
a 3D CAD model. A layer is obtained by depositing material on this horizontal contour up to the next slice. However, the layer of the original CAD model between these two horizontal slices would possibly have some curved vertical surfaces. An algorithm is developed and implemented to approximate the contour of layers with vertical curved surfaces. Generated contours forms the boundary of slice which is further meshed for mapping material information in point-wise manner. Boundary mesh generation and recursive re-triangulation algorithm is used in traditional solid modeler for homogeneous object modeling. A recursive re-triangulation sub-division algorithm is employed for more local control in a heterogeneous slice. Each triangular facet in the mesh model is sub-divided into number of sub-facets for accurate and precise material mapping in the chosen region.

<table>
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Adaptive Slicing | Uniform Slicing

![Graph showing layer thickness for a heterogeneous object](image)

**Fig. 1:** Layer thickness for a heterogeneous object: (a) HO, (b) Comparison of Adaptive and Uniform slicing, (c) Geometric Layer Thickness, (d) Material Thickness, and (e) Minimum Layer Thickness.

Post processor deals with scanning of generated slice to retrieve the geometric and material information in a generated slice. An algorithm is developed to scan the layer and retrieve the geometric and material information for rapid manufacturing of heterogeneous objects. Sliced layer information is saved in LEAF files. The information in files is composed of material information, lines, arcs and circles. This data can be easily extracted and used for RP machines.

**Examples.** The proposed algorithm for a HO is implemented and validated as shown in Fig. 2.

<table>
<thead>
<tr>
<th>Heterogeneous Object</th>
<th>Section</th>
<th>2D Cross-section</th>
<th>Meshed Region</th>
<th>Color Mapping</th>
<th>Slice of HO</th>
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**Fig. 2:** Slice generation for a heterogeneous object.

The algorithm improves performance by reducing the time for writing and reading the data and reducing file sizes for typical large datasets. The performance statistics are summarized in Tab.1 for the three sections shown in Fig. 2. The parameters i.e. size, processing and retrieving time are compared for conventional (X) and proposed algorithm (Y).
Second example demonstrating generation of a slice for the heterogeneous cylinder is shown in Fig. 3. The material composition varies linearly along horizontal axis, thus, causes material gradient exist in each slice.

![Fig. 3: Slice generation for a heterogeneous cylinder: (a) HO with Intersection Plane, (b) 2D Extracted Region, (c) Meshed Region, (d) Color Mapping against Material Information, and (e) Slice of HO.](image)

Two more examples illustrating the implementation of developed algorithm are presented in Fig.4.

![Fig. 4: Slice generation for the few heterogeneous objects.](image)

**Conclusion**

The paper is mainly focused on slice generation of a 3D HO and retrieving geometric and material information from each slice. Adaptive thickness method is used to find out the thickness of a layer considering the effect of geometry and material stair-step. Contour generation method with circular approximation is implemented to reduce the error between the contours of same slice. Boundary mesh generation procedure is adopted for meshing 2D sliced region. An algorithm for scanning a slice is proposed to get geometric and material distribution information in a slice. Efforts are made to generate fast, faithful, high quality slice generation and data retrieval system to avoid repetitive computation. The algorithm is implemented and some examples of slice generation for a heterogeneous object are discussed.

**References**


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Tab. 1: Performance statistics for a heterogeneous object shown in Fig.2.
Extended Abstract 40

Title
Identification of Weld Beads in Assemblies of B-Rep Models

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Keywords
Weld beads identification, feature recognition, virtual prototyping, cost estimation

Introduction
Current CAD systems have dedicated functionalities to model weld beads, but it is often cumbersome to use these systems. In many design departments weld beads are not modeled in the 3D representation of the product. Weld beads are only manually added to the 2D drafting documentation. This causes some important inefficiencies in the whole design and virtual prototyping process. The first regards the amount of wasted time caused by the manual insertion of the weld beads. Moreover, 3D and draft files lose alignment when product models are revised. Second, the bead definitions cannot be used in further virtual prototyping activities [1] such as structural analysis of the welded joints or cost estimation of the manufacturing process [2-3]. Such activities need a 3D representation of the beads and their links with the connected parts.

Main Idea
This paper presents a method to analyze CAD models of product assemblies in order to automatically identify possible welds among the parts using geometric recognition rules [4]. The main goal is to speed up the welding definition process as soon as the CAD model of the product is available. Then, the obtained solution can be refined manually in short time.

The algorithm is based on the following steps:
- Selection of components where beads are to be searched. Given an input assembly at any level of the product, a list of parts is produced from the product tree structure excluding non metallic parts;
- Analysis of the parts to recognize sheet metal components from the presence of recurrent pairs of cylindrical and planar faces with opposite normals and positioned at a reciprocal fixed distance, i.e. the thickness of the sheet metal (Fig 1);
- Search for contact face pairs. Pairs formed by the possible combinations of the selected parts are tested to identify contact faces, that is planar or cylindrical faces with opposite normals and null distance;

![Fig. 1: A pair of test parts in contact: a trimmed plate and a bent sheet metal.](image)

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For each pair of contact faces, the planar domains of the parametric spaces are considered (Fig 2 a). The Boolean intersection of such planar regions [5] is computed in order to use the border of the resulting areas as weld beads sources (Fig 2 b-c). Borders are subdivided on the basis of the ownership to one or the other connected part, allowing the distinction between corner and butt beads;

- Beads are then split in homogeneous portions based on the classification of the faces of the identified sheet metal parts (Fig 2 d). The geometrical analysis of the connected parts also allows a bead to be characterized in terms of thickness, type, length and accessibility.

The method is based on a set of specific rules able to evaluate if a couple of connected faces can be associated to a weld bead, and the type of possible welding. Such approach is only based on the boundary representation of the parts and the product assembly structure. In this way the geometry is not linked to a particular CAD modeling strategy and can be read from standard 3D solid formats (STEP, Acis, Parasolid).

The output is given by the bead definitions which include the 3D path of the bead, the components and the faces being connected, and the geometrical condition in the contact area.

Conclusions

Industrial products composed of sheet metal parts and beams make wide usage of welding to join parts together. The proposed algorithm has been implemented in a software system and experimented thanks to the collaboration with partner companies operating in these fields. Data has been gathered regarding a comparison between the traditional way of doing and the one supported by the proposed tool.

The main outcome regards a strong time reduction in the product virtual prototyping thanks to the time saving for the weld bead definition. Moreover, the approach reduces errors in the manufacturing documentation, i.e. drafting with welding annotations, and decreases the number of required model revisions.

References


Extended Abstract 41

Title
A computational method for bilateral symmetry recognition in asymmetrically scanned human faces

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Keywords
Reverse Engineering, symmetry plane, Iterative Closest Point, Rasterstereography, Registration, Mirroring, Asymmetry.

Introduction
One of the most important geometric features of the human face is the plane identifying its bilateral symmetry. Thanks to the possibility of having 3D data of the face, the bilateral symmetry plane can be recognised and evaluated by means of properly processed face data. The knowledge of the symmetry plane could be useful for various purposes, such as:

- face authentication (0 and 0);
- face reconstruction or cosmetic surgery for aesthetic corrections in Maxillofacial Surgery (0 and 0);
- facial asymmetry and symmetry line correlation for back pathologies in Orthopaedics and Orthodontics 0;
- facial symmetry and cognitive disorders correlations for schizophrenia diagnosis in Neurology 0.

In many practical cases the data relating to an acquired human face are incomplete and not symmetrically acquired. These limitations are mainly due to the typical technologies used in 3D geometric scanning. These technologies require that each and every part of the face should be completely visible from the device viewpoint. Considering the anatomy of the face, many parts may result in undercut and therefore may not be acquired. The portion of the face which can actually be scanned depends on the face’s distance from and orientation with respect to the scanning device. In real cases bilateral symmetry must be recognised on a partially acquired surface, which is also affected by a non-uniform point density. Thus the information which attempts to recognise human face symmetry must be extracted from an asymmetric point cloud. Other factors which may blur the symmetry recognition process can be identified in some physiognomic asymmetries of the human face, such as local damage, pimples, bumps, wrinkles, etc. Typically, the methods presented in literature are conceived and tested to analyse cases where the face is completely acquired. They fall short in the case of asymmetrically scanned data and whenever there is a non-uniform sampling density. With a view to detecting the symmetry plane of asymmetrically scanned human faces, this paper presents a new method.

Its performance, in terms of robustness and accuracy, is quantified as to the symmetry plane detection of some real test cases.

Main Idea
The proposed method. Point cloud asymmetry can be due to several reasons, some of them are due to the scanning process, other pertain to the scanned face:

- asymmetric sampling area;
- asymmetric location of the scanned points;
- global asymmetries: the human face is not an ideal, perfectly symmetric geometry as any kind of real object;
- local asymmetric features (local damage, pimples, bumps, wrinkles, etc.

Many of the methods presented in the related literature do not distinguish asymmetries of the shape from those due to the acquisition process. The proposed method is therefore designed to overcome the above-mentioned limitations. It is based on the typical mirroring-and-registration approach, properly improved to perform a robust evaluation of the bilateral facial symmetry.

The most important steps of the method are:

1) **Face Scanning.** This step is performed by means of a 3D optical geometric scanner (www.scansystems.it) which makes it possible to acquire, in a single scanning session, about 50,000 points with a density sampling of about 0.75mm.
2) **First-attempt estimation of the symmetry plane.** This phase is performed by the Principal Component Analysis (PCA) 0.
3) **Final estimation of the symmetry plane.** In this step, based on the ICP method, new definitions of the distance (Haussdorff) between the original and the mirrored meshes and of the weights which multiply these distances are introduced.

The final symmetry plane obtained approximates in the least-squares sense the midpoints of the lines connecting homologous points on the between the original and the mirrored meshes randomly chosen.
Experiments and test. The method being proposed, henceforth labelled as AQ method, has been implemented in original software, coded in MATLAB. In order to have a quantitative evaluation of the AQ method, its performance is compared with that of our implementation of the method proposed by Pan and Wu in 0 (in what follows, the Pan and Wu method). The comparison is performed by investigating the robustness and the accuracy of the methods in the analysis of 5 different acquisitions, obtained from different angles of view, of the face of 15 people which maintain the same neutral facial expression and closed eyes. By way of an example, in figure 1, one of the 15 test cases scanned by different positions, the corresponding estimated symmetry plane and the maps of the local asymmetry by the two methods are shown.

![Fig. 1: One of the 15 test cases analysed, the corresponding estimated symmetry plane and the maps of local asymmetry](image)

**Conclusion**

This paper presents a new mirroring-and-registration method for the automatic symmetry plane detection of 3D asymmetrically scanned human faces. Once the mirroring of the original data is carried out with respect to the first-attempt symmetry plane, which is estimated by the PCA method, the source point cloud and the mirrored data are registered by the ICP algorithm that minimises a new weighted function.

This method is validated by analysing some specifically-designed test cases. The results obtained show that the proposed method is practically insensitive both to asymmetrically scanned data and to non-uniformity in point cloud density. It proves to be a good tool for all those practical applications where the human face is acquired quickly and incompletely. Typical applications could be face authentication and recognition as well as clinical investigation.

**References**


Extended Abstract 42

Title
Using 3D CAD models for value visualization: an approach with SIEMENS NX HD3D Visual Reporting

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Keywords
Value driven design, systems engineering, engineering design, value visualization, color-coding.

Introduction
Recent literature in Systems Engineering [6] and Value Driven Design [2] has promoted the use of “value” as a driver for decision-making activities in an early design stage. In spite of the shortcomings in conveying lifecycle information [4], CAD represents a suitable environment [5] where engineers and designers can visually link “value” (intended as a measurable approximation of how a design solution fulfills a system stakeholders’ needs along its lifecycle [1]) to product components, to enable more value-oriented decisions in design. The authors have developed an approach that uses color-coded 3D CAD models, in SIEMENS NX HD3D Visual Reporting, to translate the results of a value analysis into visual features. The approach has been demonstrated in the development of an aero-engine intermediate compressor case (IMC) technology.

Main idea
In the case study, the IMC was broken down into 6 main parts (Fig. 1) and value models were used to assess how each part contributes in fulfilling the needs associated to an aero-engine project. Comparing these outcomes with the results obtained for a baseline and target design, each part was color-coded accordingly. Red and orange indicate parts where the value contribution is equal or below the baseline. Yellow specifies a value contribution above the baseline, but not yet satisfactory for the purpose of the project. Green indicates a contribution in line with the target. Furthermore, since in a preliminary design phase value models vary a lot in terms of quality and reliability, the approach uses tags to display the maturity [7] of the knowledge upon which the value model is built, to support decision makers.

Fig. 1: Value visualization using color-coded 3D CAD models in SIEMENS NX HD3D
To verify the proposed approach, the authors have analyzed the designers’ behavior during design episodes, both by designing and conducting experiments using protocol analysis [3], and by means of a Likert-scale questionnaire. The experiments featured design sessions with researchers and students from a Master Programme in product development. The objective was to measure the effectiveness of color-coded CAD models as means for raising awareness on value information in preliminary design, by comparing them with other forms of visualization, such as color-coded tables.

![Fig. 2: Results from experimentation activities on the color-coded models](image)

The experiments show that teams with color-coded 3D models dedicate:

- 135% more time for analyzing the value reports, compared to color-coded tables;
- 26% more time for analyzing the design problem, and 21% more time for proposing and clarifying solutions;
- 31% less time for retracting previous solutions (suitable solution concepts are indentified in less iterations).

Conclusions
The study highlighted a set of preferences for value visualisation, which were used as a basis for the development of the methodological/technological approach prototyped in SIEMENS NX HD3D Visual Reporting. The results of the verification activities performed so far indicate that color-coding increases the decision makers’ awareness of value-related information during preliminary design, stimulating the analysis of the value assessment report and the discussion on value-related matters. Such results will be further validated by means of new experiments with industrial engineers and designers, in a real working scenario.

Acknowledgments
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References
Extended Abstract 43

Title
Methods Of CAD Based Automation And Simulation By The Example Of Virtual Stone Chipping Testing

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Keywords
Virtual Prototyping, Computer Aided Design, Macro Programming, Product Data Management

Introduction
Nowadays companies are faced with constantly increasing requirements for quality conditions which have to be realized in even shorter development cycles. The huge product diversity, permanent changing boundary conditions and the high complexity of products represent an additional challenge in the automotive industry. In order to meet the desire for better quality and still to achieve competitiveness, costs have to be kept minimal and development cycles have to be optimized. This can be achieved through the use of new, modern CAD based development methods and tools to ensure a flexible, changeable and efficient design and production engineering. An efficient and modifiable development of vehicles can be realized with the help of modern IT-based engineering tools. Thus companies can provide the necessary quality of their products in a relatively short time at low costs. With the principles of simultaneous engineering, frontloading and the help of computer aided engineering (CAE) applications enormous time and cost savings are possible. This is especially visible in the early phases of the development process. The earlier knowledge is generated and detailed work is realized, the more successful and better the final results can be. The optimization of the automotive development process is supported by the integration of simulations during the individual steps. In this way, parametric associative computer aided design provides a foundation for a successful simulation, [1], [2], [3].

Main Idea
The application of virtual product development in early stages of the vehicle development cycle supports a replacement of expensive hardware prototype tests. The time saving in case of prototype research is visualized in the following Fig. 1, [4].

An example of a CAD based virtual simulation in the automotive development is shown by a method for virtual stone chipping testing on vehicle bodies. Stones which are stirred up by the tires and discarded can damage the vehicle body and other parts. In this way, stone chipping presents an important topic in the field of corrosion protection in the automotive industry. Tests which are performed on hardware prototypes are expensive and often too late to enable efficient design changes to the body-in-white. An optimization of the development process in case of stone chipping with attendant cost savings can be realized by a virtual investigation in early stages of vehicle development. The difficult measurement of factors and the complexity of stone chipping mechanism represent a challenge for the vehicle development. As a basis for the stone chipping simulation on automotive body-in-white, the vehicle exterior surfaces have to be prepared by creating a shape assemblage from the numerous of individual vehicle body shape surface elements. In automotive engineering different programs and tools are used in the course of vehicle development included in the styling and design phase. During the concept phase in the development process vehicle body surfaces are designed with the aid of CAD external styling software, which can lead to data defects, e.g. tolerance deviations. In
this way, the joining of such vehicle body surface elements often produces topological errors because of incompatible shapes. Of course the option to optimize the product data management by using neutral data formats supports the solution of this challenge, but to solve the assemblage error an algorithm has to be included by a macro programming to ensure an efficient preprocessing tool [3], [5], [6].

After joining the surface elements into an assemblage with satisfying data quality, a geometrical tyre substitution is created. An adequate macro programming guides the user through the individual steps. Parameters are created by the input in terms of tyre data and the geometrical objects are connected to them. So it is possible to quickly generate a changeable geometrical tyre substitution. Stones, which adhere on the tyre surface or stick in the profile under real life conditions, are simulated by specific points on the geometrical tyre substitution. The launching is visualized by trajectories in terms of tangents or parables. For that purpose lines are constructed in different ways. Knowledgeware in CAD programs is a good option to handle the target of automated geometry creation and verification. Therefore, the implementation in terms of rules and assoziative parametric construction is necessary. The impact of the launched stones onto the vehicle body is simulated by blending the trajectories with the body shape assemblage. Subsequently there are possibilities to evaluate the angle of impact onto the vehicle body by means of an automated program, which enables a damage conclusion for the stone impact evaluation in the way of a postprocessing tool, as shown in Fig.2, [3].

![Image](image-url)

**Fig. 1: Visualization of result of a virtual stone-chipping investigation [3]**

**Conclusions**

The implementation of virtual development tools supports effective development processes to discharge the increasing pressure based on the high requirements in the automotive industry. Due to new generated engineering methods it is possible to save costs and development time by shifting important decisions to earlier stages in the development process. This effect results from the compliance of arrangements in the case of frontloading. For that purpose the combination of computer aided design and automation is indispensable. The present publication includes an application of problem oriented automated knowledge based engineering methods within commercial CAD software. The virtual evaluation of stone chipping represents an interesting application of enhanced geometry based simulation, which is able to support automotive development processes in a virtual environment.

**References**

Extended Abstract 44

Title
Optimization of assembly processes of an automobile wire harness

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Keywords
Computer Aided Manufacturing, Layout optimization, Jigs layout, Assembly of a automobile wire harness

Introduction
A wire harness is an assembly of cables or wires which transmit signals or electrical power. To protect the cables and reduce time to install a harness to a product, the cables are bound together by tape, tube, sleeve or other ways. A wire harness is used in various kinds of products. Among them, an automobile is a major example. In automobile industries, a wire harness is manually manufactured by using a workbench with jigs in the form of a fork shown in Fig.1 according to the following procedure. (1) Cables are cut to the desired length and the end of the cables is terminated. (2) The cables are routed through jigs. Jigs look like a fork and have a role in holding routed cables during assembly processes. (3) The end of the cables is inserted into connector housings. (4) Finally, cables are bound by tapes. Although automobile manufacturing processes are highly automated in these days, a wire harness still needs to be manufactured by hands.

To design efficient assembly processes of a wire harness, automotive parts suppliers developed CAD/CAM based systems [1] [3]. However, even if these methods are used, design of assembly processes still needs to be done by engineers by trial and error. Thus, the level of engineers has a large impact on efficiency of assembly processes. Therefore, in order to design efficient assembly processes without expertise of veteran engineers and trial and error, a new design method based on optimization is required. This paper focuses on the process a worker tapes cables and develop optimization of a jigs layout on a workbench to minimize working time.

Main Idea
Right of Fig.1 shows the model of a wire harness on a workbench. Node N is a branch point / end of the harness. Jigs in the form of a fork are placed at each node. The harness between two nodes is named edge E. The length, the diameter and the angle of the edge E_j are l_j, d_j and θ_j respectively. The angle θ_j is formed by a horizontal line and edge E_j in anticlockwise direction. The edge consisting of many cables is named “Main edge” whereas other edges are named “Branch edge”. At the optimization stage, the number of nodes and edges, the length and the diameter of each edge are given conditions whereas the angle of each edge is used as a design variable.

Fig. 1: A workbench for assembly of an automobile wire harness (Left) and Model of a wire harness on a workbench (Right).

Total working time \( T \), the time it takes to tape every edge, is the objective function at the optimization stage. Total working time \( T \) is defined by the below equation.

\[
T = \sum_{i=1}^{N} t_i \omega_i
\]
where, $t_i$ is basic operation time it takes to tape the edge $E_i$. Basic working time $t_i$ is calculated by left of Table 1 using the length $l_i$ and the diameter $d_i$. $a_i$ is the level of difficulty to tape the edge $E_i$. As described above, if the angle between two edges is small, it becomes difficult to tape these edges. Level of difficulty $a_i$ is calculated by right of Table 1 using the angle between neighborhood edges and the diameter $d_i$. In this research, genetic algorithm is used to minimize the total operation time $T$

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<td>30</td>
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<td>45</td>
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<tr>
<td>75</td>
<td>1.6</td>
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</table>

Tab. 1: Tables for calculating basic operation time (Left) and level of difficulty (Right)

There are several constraint conditions due to design requirements of a wire harness and workability of assembly process.

- It is desirable that main edges are arranged linearly
- Edges should not cross each other
- Edges should not be beyond the area of the workbench.
- Adjacency relationship among edges at each node is given condition and should not be changed

Results
To test effectiveness of the proposed method, layout of the wire harness for a compact car is optimized using the proposed method. As shown in left of Fig.3, the harness consists of 35 edges and 36 nodes. The values described in left of Fig.2 are length and diameter of each edge. As for parameters of GA, Population is 120, mutation rate is 0.01 and terminal generation is 300.

![Wire harness model](image)

Fig. 2: Wire harness model (Left) and obtained optimal layout (Right)

Right of Fig.2 shows the obtained optimal layout. As shown in this figure, Adjacency relationship among edges at every node is not changed. Total operation time $T$ is 168 second.

Conclusions
To enable more efficient assembly processes of an automobile wire harness, optimization of layout of jigs and a harness on a workbench is proposed in this research.
Extended abstract 45

Title
Unsupervised shape classification of convexly touching coated parts with different geometries

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Keywords
Shape classification, Convex-touching objects, Computer Aided Visual Inspection

Introduction
Geometries that do not belong to the currently inspected geometry (novelty part) have to be rejected during inspection in coating industries. The coated part’s geometry is not always the same for all the lots. The parts may be touching or overlapping and hence they have to be separated in segmentation before extracting shape information. The shape feature extraction from the segmented image has to be robust enough to capture the difference. Since the geometry that we are looking for is not known, this is an unsupervised shape classification. Hence the solution is not trivial.

A vast number of segmentation methods have been proposed in literature [6]. There are some methods for separating the touching particles, for example, the morphological operations [1], the concavities based algorithm [4] and Fourier elliptical descriptor [2], etc. K means is a widely used method in unsupervised classification [3]. A vast number of techniques are employed in geometry inspection [5]. The problem considered here is unique and the above state of the art algorithms are tested and combined forming a novel framework.

Development of inspection framework
Images of various combinations of defective pieces were captured in laboratory image acquisition setup (Figure 1a). A ring LED light is used as illumination for the image acquisition. Various parts such as nut, bolt, armature, screws along with few novelty parts are captured as colour images with the input from the industry. Figure 1b shows one such image with nuts as non-defective and screws as a novelty part. The parts have to be segmented from the background and touching objects have to be separated. From the separated image certain shape features have to be extracted. With those features the parts has to be clustered as novelty and non-defective without any priori information. The techniques used at each step are explained in the following sections.

Fig.1. Image acquisition and segmentation (a) Laboratory setup (b) Image with novelty parts (c) Otsu segmentation (d) Binary Image after morphological operations (e) Colours showing convexly touching objects

Segmentation. The segmentation of the parts from the background is carried out using Otsu method and the result is shown in Figure 1c. The binary image obtained is further subjected to morphological operations such as opening, closing and filling to remove the artefacts and shown in Figure 1d.

Border Smoothening. In the segmented binary image, few parts (appearing as white blobs) are touching (Figure 1e). These blobs have to be separated assuming that they touch convexly. The curvature at those touching points significantly differs from rest of the points on the border of the white blobs. To obtain the curvature a smooth border is needed. To transform the blobs with a smooth border the following procedure was followed. The boundaries were extracted from the binary image using the canny edge operator. The shape signature of the boundaries can be described by elliptic Fourier descriptor. The chain code was calculated from the boundary image. The chain code was converted to Fourier domain by Fast Fourier Transform. Only 50% of the frequencies are retained while it is converted to chain code by Inverse Fast Fourier Transform. The chain code was converted back to the original image.
to binary image with smoothened borders. By eliminating the high frequency information smoothened borders was obtained.  

**Curvature and Convexly-touching points.** The curvature was then calculated for all points in the border. Seven points around the considered point is taken and least square fitted with lines to calculate the curvature. Points below threshold of -0.01 curvatures are taken as convex points. The curvature varying along the border of a convexly touching blob is shown in Figure 2a. If more than two objects are touching the corresponding points to be separated by ellipse-fitting. The touching parts are then separated along the nodal points as shown in Figure 2b.  

**Unsupervised classification.** The area of each blob is then calculated. The medial axis or skeleton is calculated using thinning operation (Figure 2c). The area and medial axis were considered as features and clustered with unsupervised k-means algorithm. The k was selected as 2 because only the novelty had to be classified from the rest. The classifier returns a null cluster when there is no novelty part. The result of shape classification is shown in Figure 2d.  

**Limitations.** The limitations of the proposed inspection framework are occlusion, overlap of parts, high intensity illumination, assumption of convex shaped objects and mix-up of more geometry. Any holes in the object should be free of other objects. Bright spots degrade the segmentation and in turn may affect the overall efficiency of the method.

![Fig.2. Corner detection and shape classification (a) Curvature along the smoothened border of 2 touching objects (b) Touching objects – separated (c) Skeleton/ Medial axis (d) Unsupervised classification by k-means and labelling](image)

**Conclusions**

The novelty part detection problem in industry is prototyped in laboratory environment. Images of various geometries like nut, bolt, armature, screws were captured along with various novelty geometries. The segmentation of the geometries from background is based on histogram properties. Fourier elliptic shape descriptor along with curvature information works well to separate different or same touching geometries. The feature space is contributed by area and skeleton of the geometries providing a large intra-class variance and hence k-means algorithm classifies the shapes with high accuracy. The proposed algorithm works well on a broad variety of situations such as different geometries, uniform scaling and rotation of the parts. Overall the proposed inspection scheme forms a generic novel framework that has a potential for automation in industries.

**References**


Extended Abstract 46

Title
Virtual Simulation of Assembly Sequencing using Disassembly Method

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Keywords
Assembly sequence, Virtual simulation, Disassembly,

Introduction
Assembly is a process whereby individually parts are pieced together to form the final product. While these individual parts are designed to be assembled together in a fixed geometrical manner, the process of placing them together can be complicated. The ability to visualize an assembly process through virtual simulation is important for the evaluation of the assembly processes without building one actual assembly line. While there exists various methods [1, 2] to solve for the sequence for a given assembly, there are little attempts to bring assembly sequencing directly to the CAD platforms where the assembly model is first conceived. The possibility of having an assembly sequencer on CAD platforms will provide additional dimension of visualization in the mechanical design process. The objective of this paper is to explore the feasibility of implementing an assembly sequencing on a popular CAD platform, Solidworks, as a macro by utilizing its API to extract geometrical information as well as to determine the assembly sequence. For assembly of a product using CAD software platform, the mating relationship between individual components must be considered for the product to be assembled. Taking this information into consideration, an easier approach is by considering the disassembly process. The main approach in this paper used to solve a CAD model for its assembly sequences is first solve for the disassembly sequence which based on the Gaussian sphere concept as previously developed by [3, 4]. To demonstrate the proposed approach, implementation is carried out using Virtual LEGO® bricks as the subject components of the assembly.

Main Section
Disassembly using the concept of the Gaussian sphere is utilized in this paper as a ‘reverse engineering’ approach to resolve assembly sequences of a given CAD assembly. For the problem of disassembly, the given assembly will be first examined for its component make-up to determine contact surfaces and direction of removal. Contact surfaces are barriers to restriction for every component. By retrieving the relative position of its every contact surface, obstruction to the movement in certain directions can be determined and hence the mobility of the component in the assembly is known. The mobility of each component can be represented by degree of freedom (DOF) of Gaussian sphere as shown in Fig. 1. The Gaussian sphere is a theoretical sphere that encompasses the object as its centre. It serves as a projection to indicate the possible direction of object movement. If the direction of every contact surface of the component is taken in union with its Gaussian sphere such that the direction of each contact surface takes a cut in the sphere, the section of the Gaussian sphere that remains will represent the possible DOF of the component. Sequencing the paths of disassembly can subsequently be assigned.

For the sake of simplification and illustrating the proposed concept, this work has chosen the simple virtual LEGO brick for the assembly component. As the surface of the LEGO brick is flat and each brick is the same with six faces, it simplifies the issue of surface contact and orientation. The LEGO brick is slightly modified from the round connectors at the top and bottom to the square connectors in this work as shown in Figure 2. The flat surfaces will simplify the variations of surfaces on the component itself such that all faces on the component are orthogonal to one another and hence limited to only 6 directions (+x, +y, +z, -x, -y, -z) instead of the full 360° range of movement. This will reduce the possible variations in the assembly sequencing algorithm. This general disassembly is applicable to any assembly that has regular components of any faces with flat surfaces besides the LEGO brick. Movement of components will be also limited to translation only. The algorithm could be complicated for objects with more complex shapes as full 360° orientations are involved.

By using API functions in SolidWorks, geometrical and entity data can be retrieved from the input CAD file, processed through the algorithm to generate the appropriate assembly/disassembly sequencing. Programming of the algorithm is done via SolidWorks as a macro in the built in Visual Basic for Applications interface. All visualization of the assembly sequencing is presented on the SolidWorks Graphical User Interface.
An algorithm for a general disassembly of components based on contact faces is first proposed. However, the runtime of this algorithm increases exponentially with the increase of components in the assembly. Preliminary test runs showed that the extensive use of API calls has tremendously slowed the process time. An improved algorithm is proposed as follows.

1. Get component array from the assembly CAD file.
2. Get component array of Y-positions with highest and lowest Y-positions to find the height of the assembly.
3. Determine final Y-position of the assembly. Five approaches are proposed to allocate the final y position. These are Type 1: Start from top; Type 2: Start from bottom; Type 3: Work towards geometrical centre; Type 4: Work towards component-weighted density mean; and Type 5: Work towards the highest density of components.
4. Select assembled component furthest away from final Y-position.
5. Check DOF and move component.
6. Select next component.

The proposed algorithm has shown that its runtime is almost negligible unlike in the preliminary test runs.

Case Study

Few case studies have been implemented with very little runtime to achieve automated assembly sequence. One examples of the case studies with a 4-legged table assembled using 45 varying LEGO bricks as shown in Fig. 3 has been carried out. As the table top consists of larger number of components interlocking via a two layer assembly, the component density is thus higher and concentrated at the higher end of the y axis. By inspection, one would start assembling the tabletop followed by the four individual legs as the table top will provide the foundation for connecting the legs of the table. In order to create an assembly sequence that starts from the top, disassembly should start from the bottom.

Conclusions

This paper presents an approach that uses the disassembly method based on Gaussian sphere through virtual simulation to derive an assembly sequence. The disassembly method uses virtual LEGO bricks with a defined degree of freedom as the components for assembly on a popular CAD platform, SolidWorks. The proposed algorithm has been shown to be feasible with case studies. To extend the algorithm for objects with more complex shapes, one will see the increase in assembly sequencing variations. Further studies could be conducted on various types of surfaces or LEGO bricks in the market.

References


Fig. 1: Determining the freedom of movement of a component starting from a full Gaussian sphere

Fig. 2: A modified virtual LEGO® brick used

Fig. 3: (a) Assembled table and (b) Its approximate component density profile
Extended Abstract 47

Title
Computer-Aided 3D ICs Layout Design

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Keywords
Computer Aided Design, 3D ICs, Computational Intelligence, Optimization, Shape Grammar, 3D Floorplanning

Introduction
The first stage in ICs design is the layout. The task is to pack all the given circuit elements in a chip without violating design rules, so that the circuit performs well and the production yield is high. All the elements are rectangular modules of fixed orientation, height and width. The minimum bounding box of a packing is called the chip [4]. Floorplanning is a well studied problem for 2D ICs but in 3D no efficient algorithm solving the problem exists.

This paper presents a framework for visual kind of intelligent 3D layout design with shape grammars and computational intelligence methods. The principal assumption for the framework is that the optimization technique and the shape grammar geometric representation are problem independent while goals and constraints vary for different problems. An optimization search algorithm should take the problem formulation and identify promising solutions by evaluating design alternatives and evolving designs states. To verify the proposed approach, a dedicated application PerfectShape was implemented. The examples presented in the paper are generated with a use of the original software.

Main Idea
We propose a framework for 3D layout design that benefits from the dynamic character of the design environment. The reach design context is moderated by: (1) Designer, (2) Shape Grammar, (3) Design knowledge – goals and constraints, and (4) Derivation Controller. The aim is to generate feasible designs that best meet given design criteria. We combine both the descriptive and the generative power of shape grammars, and stochastic optimization algorithms which are able to navigate nonlinear and multi-modal spaces. The proposed solution is methodologically advanced and easily reconfigurable. The approach is presented by the example of a 3D IC layout problem.

A shape grammar is a production rule-based system which derives designs by successive application of shape transformation rules to some evolving shape configuration [1]. We decided to encrypt a low level of knowledge in a grammar itself and use a separate controlling mechanism to conduct visual computations, namely goals and constraints, and derivation controller. A single constraint is a predicate that applied to a shape returns true or false. A single goal is also a predicate but opposite to a constraint it can be satisfied to some extent. The explicit impact factor of a single goal to a design evaluation score is moderated by a derivation controller. A derivation controller runs a generation of a potential solution. Every generation step requires three decisions to be made. Firstly, a rule from a set of applicable rules has to be selected. Secondly, one of the possible shape configurations we are going to apply the rule to has to be chosen. We have established four different methods of a rule embedding (Tab. 1) and as we can see in Fig. 1 the rule embedding method has an essential influence on the final design. Finally, the decision either to approve or to reject a generation step has to be made. The last step, includes two stages: constraints validation and goals evaluation. We look for a design solution until stop criteria are met. The stop criteria should include the maximum iteration number and some design evaluation value conditions.

<table>
<thead>
<tr>
<th>Embedding</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Execute first admissible</td>
<td>a rule is applied to the first admissible shape configuration, if one is recognized</td>
</tr>
<tr>
<td>b) Execute last</td>
<td>a rule is tried to being applied to the part of the design which come into being during the last execution step</td>
</tr>
<tr>
<td>c) Execute random</td>
<td>a rule is applied to randomly selected one from the all admissible shape configurations</td>
</tr>
<tr>
<td>d) Execute all</td>
<td>a rule is applied to all admissible shape configurations</td>
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</tbody>
</table>

Tab. 1: Rule embedding methods.
While investigating the circuits layout problem it appeared that many of the constraints are geometrical in nature. E.g., all the circuit elements must be placed on a given chip \((\text{area constraint})\) without overlap \((\text{no intersection constraint})\). If an IC design meets all the constraints, goals evaluation is performed. At this stage of our research we focus mainly on the goals which are geometrical in nature and first of all, we are looking for the minimal packing \((\text{minimal space goal})\).

In our approach, we propose to select a rule with some assigned probability which is adaptively changing during the course of derivations. The implemented rule selection mechanism is based on a well known, in the field of evolutionary computations (EC), roulette wheel selection. We assign some startup rules weights (corresponding to probabilities), equivalent to a fitness function value in EC, to all rules. In an IC design, the weights values decrease proportionally to the number of generated components. In this way, we not only have some rule selection controlling mechanism, but we reach a goal of generating all the required components as well. In order to find the right rule application we check different execute random \((\text{Tab. 1})\) applications for specified number of tries. After all tries, we select the application with the highest evaluation value. If the obtained new evaluation value is higher than the one before the execution, the application is committed. If not, we can use simulated annealing machine learning method to decide whether to accept or to reject the generation step. Some preliminary results for a 3D IC layout design task are in Fig. 2.

Conclusions

The aim of the presented research is to build a flexible software architecture framework which will enable solving the 3D layout problem for different engineering design assignments. The proposed solution has to be both methodologically advanced and easily reconfigurable. There are many reasons why the approach is applied to the 3D ICs layout design. First of all, the 3D ICs floorplanning effective computer-aided design is not only up-to-date but very challenging one as well. The selected problem design space contains so various goals and constraints that successful application in this domain will confirm the general usefulness of the elaborated framework.

Acknowledgements

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References

Extended Abstract 48

Title
Optimal Rotational Symmetry Cell Mesh Construction for FE Analysis by Symmetry-constrained Local Delaunay Refinement

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Keywords
Finite Element Analysis, Symmetry Cell, Rotational Symmetry, Delaunay Refinement

Introduction
In performing finite element (FE) analysis for an engineered design, a symmetric model is usually reduced to a symmetry cell, a minimal part of the model from which the whole model can be restored from its symmetry pattern. The mesh of the symmetry cell is then generated separately after the cell extraction. Exploitation of such symmetry properties helps reduce the computational complexity of downstream tasks of mesh generation and engineering analysis, and saves memory usage. A good example for extracting the symmetry cells and to use it for facilitating FE analysis is referred to [3]. However, due to the separation of the symmetry cell extraction and the mesh generation, the mesh generated following such a procedure is usually not optimal in the sense that their mesh number is not minimal at certain quality requirements, and thus is not very computationally efficient.

In order to resolve this issue, a novel approach is proposed in this paper to construct an optimal symmetry cell mesh (in its mesh element number) for a rotationally symmetric CAD model in boundary representation. The optimality is mainly achieved by simultaneously extracting the symmetry cell and generating its associated mesh form. In such way, the global symmetry information of the whole model is maximally used for mesh quality, and the mesh is only generated for the symmetry cell, instead of the whole model, for computational efficiency.

Main Idea
Following previous work [1], a symmetry cell mesh of a rotationally symmetric model is size-optimal, or optimal for simplicity, if an optimal mesh of the global model can be trivially produced by performing the rotation transformation on it; see Fig. 1.

![Fig. 1: Symmetry cell of a 4-fold rotationally symmetric mesh.](image)

The main idea to achieve the optimal symmetry cell mesh is to use a symmetry-constrained local Delaunay refinement, built on previous work on Delaunay refinement, specifically, size optimal mesh generation by Delaunay refinement [1-2], [4], and symmetry-preserved meshing via orbit insertion [5].

The approach is illustrated in 2D case as follows. Let X be an $n$-fold rotationally symmetric model, $\theta$ the symmetry angle, and $o$ the centroid of X. The symmetry group of X is $C_n = \{R_0, R_1, ..., R_{n-1}\}$, where $R_i (i \in \mathbb{N}, 0 < i < n)$ is a rotational transformation of $i \times \theta$ degrees about $o$. A Delaunay triangulation $T$ of X and a partial triangulation $PT$ of $X$ are constructed as follows:

1. Compute the initial Delaunay triangulation $T_0$ of X. Take a connected symmetry cell of $T_0$ as $PT_0$. Mark boundary edges of $PT_0$ that lie in the interior of $T_0$ as symmetry edges. Two symmetry edges form a pair if they can be transformed into each other by a transformation in $C_n$.
(2) Iteratively refine $T_0$ by inserting new vertices. In the $i$th ($i=0, 1, 2...$) iteration step, obtain $T_{i+1}$ from $T_i$ as follows: (a) Locate a new vertex $p$ to be inserted following the rules in [1]. Apply the $n$ transformations in $C_i$ to $p$ to get $n$ symmetric vertices. (b) Insert these $n$ symmetric vertices into $T_i$ and update $T_i$ to maintain Delaunayness. (c) Let $T_{i+1}=T_i$.

(3) $PT_0$ is refined synchronously with $T_0$. Each time $T_i$ is refined, $PT_i$ is also refined to get $PT_{i+1}$ as follows: (a) Find a vertex $p'$ among the $n$ symmetric vertices that lies in the interior of $PT_i$. (b) Insert $p'$ into $PT_i$ and update $PT_i$ by triangle splitting and edge flipping. If $p'$ lies on a symmetry edge $e$, move the triangle on $e$'s paired symmetry edge onto $e$ before splitting. If a symmetry edge $e$ is to be flipped, move the triangle on $e$'s paired symmetry edge onto $e$ before flipping. Movements of triangles on symmetry edges are shown in Fig. 2. After splitting and flipping, old symmetry edge pairs disappear and new symmetry edge pairs are formed. (c) Let $PT_{i+1}=PT_i$.

(4) When all triangles in $T_i$ satisfy the required quality criterion, stop refinement process and let $PT=PT_i, T=T_i$.

![Fig. 2: Triangle movements on symmetry edges](image-url)

Fig. 2: Triangle movements on symmetry edges: (a) Triangulation with symmetry edge to be flipped, (b) Triangulation after move of triangle, (c) Triangulation after edge flipping.

It is proved in this paper that $T$ is optimal and $PT$ is a symmetry cell of $T$, so that $PT$ can be taken as an optimal symmetry cell of $X$. The purpose of constructing $T$ is to prove the optimality. In actual operation, the construction of $T$ is not necessary, because the information provided by $PT$ and its symmetry edges are sufficient to locate a new inserting vertex.

Extension of the method to 3D case is also discussed. The method is implemented based on two open source libraries Triangle and Tetgen. Both 2D and 3D models are used to test the method.

Conclusions

A novel automatic approach for constructing optimal symmetry cell mesh of a rotationally symmetric model is proposed in this paper. By simultaneously extracting the symmetry cell and generating its associated mesh form using the symmetry-constrained local Delaunay triangulation, it has the following advantages: (1) Mesh quality is controllable and the mesh element number is minimal at certain quality requirement. (2) Computational efficiency is achieved by only local mesh generation. (3) The generated meshes can be used directly as input to downstream FE analysis procedure.

References


Extended Abstract 49

Title
An application of enhanced knowledge-based design in automotive seat development

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Keyword
Knowledge-based design, KBE, parametric-associative design, integrated CAD

Introduction
Development of comprehensive and complex products, like seats in automotive engineering, is characterized by numerous interconnected development processes which often have to be performed simultaneously. The ongoing trend towards a wide range of product variances and functionalities, as results of increasing market requirements, leads to continuously reduced development times. Today, several virtual development tools and methods are offered and applied to accomplish those challenges. In this way, specific tasks in design and simulation departments can be performed independently in a high level of detail by use of appropriated engineering software. However, if the development of components or products, that are characterized by manifold interdependent influencing factors, is performed in different environments or programs, a continuously alignment of the actual working status is indispensable. Considering iterative optimization procedures, this fact leads to an increased working effort and mainly prerequisites the know-how of participating engineers to understand the influencing factors and their dependencies. In addition, several requirements of boundary conditions which stem from internal product specifications or external directives have to be fulfilled.

The present publication treats these characteristics during development of automotive seats, representative as one of the most complex components in automotive development. The challenge is to develop a virtual environment based on the approach of centralized 3D-CAD master models, as discussed in [1], which quickly allow the simultaneous representation and alignment of involved parts and components. As an enhancement of already carried out investigations [2], the present approach focuses on the application of knowledge-based methods by use of parametric-associative functions of modern 3D-CAD software in combination with efficient data-management, to handle the extensive quantity of information.

Main Idea
An integrated 3D-CAD master model which contains certain associative interlinked components with direct functional and geometric interdependencies states the basis for the present approach. In this way this master model allows the alignment and representation of different relations in a unique environment. In case of seat development, the influencing factors mainly stem from legal requirements, ergonomic tasks, safety and comfort issues and aspects of styling development. One idea of this approach is to implement the huge amount of detailed impacts by use of knowledge-based engineering (KBE) methods.

Modern parametric-associative CAD software offers a wide range of KBE-methods. While initially the intention of KBE was the reduction of periodic design tasks, today the focus of KBE is positioned in the area of process and data management. In this way there are numerous possibilities to integrate knowledge into CAD-documents which reach from parameter value checks over rule-based mathematic definitions up to API-based programming (Application Programming Interface), [4].

Regarding the present approach, automotive seat-related requirements from legislation and standards of different markets and regions are implemented by definition of mathematical routines using KBE-rules and checks which control the geometric parameters in generic structured documents. This leads to the reduction of part numbers and consequently to a declination of required memory which states an important fact during the work with master models. Highly integrated master models with parametric controlled geometry require many input parameters and simultaneously cause a higher risk of geometrical inconsistencies. An important key aspect of this approach lies in its ability of an active prevention of geometric conflicts, based on mathematic equation systems and conditions using the input parameters and rule-based KBE-tools. To give an example, the CAD-based evaluation of a swept volume of a seatbelt which is winded over a seat back, requires many preconditions to prevent geometric errors in terms of geometric inconsistency. In this way the smart application of KBE-based definitions allow the generic design of kinematic-based procedures too. A further feature of the present approach treats the replacement of simulation procedures by CAD-based methods. In particular, the development of a seatbelt track over the passenger’s body is an important fact which mainly depends on the location of the belt anchorages, the dimension of the belt deflection brackets, the size of the
passenger (dummy) or a possible child restraint system and the actual seat position inside its travel path. The present integrated approach enables the calculation of the belt track based on implemented mathematic optimization algorithms with a minimum entire belt length as optimization criteria. Changing any parameters regarding previously mentioned development tasks, like the dummy position or the location of belt anchorages, automatically executes the optimization routine to calculate the actual belt properties which can lead to an intensive reduction of development cycle time.

A main challenge of such integrated approaches is the big amount of working- and input-parameters, which have to be put in manually by the users. The described implemented knowledge-based methods, that automatically manage geometry representation, are working in background. In this way, the applied methods provide a user-friendly handling for engineers, who are not primarily specialized in the applied KBE algorithms.

Key aspect of the present approach is to support the engineers managing all parameters in an efficient way by applying a user interface (GUI) based on API-programming routines (Fig. 1). Furthermore, this GUI controls a bidirectional interface to a database and enables an efficient archiving and tracking of parameters. Not only input parameters but also calculated parameters, e.g. belt length, are stored in the coupled database, which simultaneously serves as centralized collaborative object. Besides the handling of parameters, the approach filters numerous geometry checks of corresponding CAD-documents geometry healthiness and prepares them clearly-arranged in the GUI. As a precondition for integrating this approach to modern virtual development processes, an implemented data-interface enables the import and export of CAD-data to traditional PDM-systems or even to flexible data-structures in early concept development phases, [1].

![Fig. 1: Architecture of present approach.](image)

Conclusions
The presented approach is applied in automotive seat development and leads to an increase of working efficiency, in particular in terms of collaborative engineering and early development phases. The integrated master model supports initial development stages with parametric controlled geometry including high degrees of freedom for concept modeling. Furthermore the results of the replaced belt track simulation by 3D-CAD can reach a good correlation to test results in hardware-based development or the application of extensive virtual human models. In this way it is demonstrated, that a smart combination of different levels of KBE methods and interfaces enables an efficient process control by use of integrated automatisms and therefore improves the efficiency of product development cycles.

References
Extended Abstract 51

Title
Improved Spiral High Speed Machining of Pockets with Islands

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Keywords
High-Speed Pocket Machining, Smooth Tool Path, Spiral Tool Path, Voronoi Diagram, Optimization

Introduction
In pocket machining a numerically controlled milling machine is used to cut a cavity out of a solid material a layer at a time by moving the tool along a path. Most cutting moves are constrained to planes parallel to two coordinate axes, e.g., parallel to the xy-plane, thus rendering the computation of tool paths for pocketing a geometric problem in two dimensions (2D): The tool can be regarded as a circular disk, and computing a tool path means finding a path in 2D such that the swept volume of the disk covers the 2D shape that models the pocket.

When using high speed machining (HSM), the spindle rotation speed and the feedrate are higher than for conventional milling in order to minimize the manufacturing time without a decrease in the part quality. The increased speeds and feedrates of HSM impose new constraints on the tool path: Sharp corners of the tool path, slotting cuts and a rapidly changing tool load are to be avoided since they may result in an increased tool wear and decreased part quality.

Interestingly, little is known about the generation of high-quality HSM tool paths for pocket machining. Bieterman and Sandstrom [1] use the solution of an elliptic partial differential equation to compute smooth tool paths that spiral outwards from a center of the pocket to its boundary. Their method seems to be targeted at "nearly convex" pocket shapes, and our tests made it evident that it is difficult to apply their method to more general pockets. In [4], we employed Voronoi diagrams to compute a smooth spiral-out tool path for general pockets bounded by straight-line segments and circular arcs.

Main Idea
It is obvious that the shape of the pocket has a great influence on the suitability of a spiral tool path for HSM: If the pocket is long but very narrow or contains bottlenecks then one spiral path may be less than ideal, and it might be better to find a decomposition of the pocket and to machine the resulting sub-pockets by separate spirals. It is also obvious that the choice of the start point of the spiral ought to be chosen deliberately, leaving room for a second improvement if the start is not fixed due to user or process requirements. Therefore, we suggest geometric heuristics for decomposing a complex pocket into sub-pockets that are better suited for HSM, and for choosing the start point of a spiral tool path within such a sub-pocket.

As in our prior work [4], we make extensive use of the Voronoi diagram of the pocket boundary. Roughly, the Voronoi diagram of straight-line segments and circular arcs as input sites partitions the plane into regions such that every region corresponds to a site and such that it consists of all points closer to that site than to any other site. From the Voronoi diagram the medial axis (MA) of the pocket boundary is obtained easily since it forms a subset of the Voronoi diagram. (See [2] for a formal definition and detailed discussion of Voronoi diagram and medial axis.)

Let R be the start of the spiral path. For the sake of simplicity, suppose that R lies on the MA. (This restriction can be waived.) For a pocket bounded by one contour (and, thus, without islands) the MA can be interpreted as a geometric tree with R as root. Our spiral paths start at R and spiral out until the boundary of the pocket is reached, thereby moving around for m times within m laps. (Machining is finished by one last pass along the pocket contour.) The number m of laps of a spiral tool path depends on the tool diameter, on the maximum step-over distance allowed by the user, and on the position of R within MA.

We compute the distance of R from every leaf of MA. (The distance is given by the length of the curved path on MA that leads from R to the leaf; it can be approximated easily by considering a polygonal chain instead of the actual curved path.) A mathematical analysis shows that the number of laps is (close to) minimum if the inter-lap distances are as uniform as possible and if R is "distance-balanced": Two leaves of MA ought to have equal distance from R, and this distance is greater than the distance to any other leaf of MA. A standard graph-theoretic search on MA allows us to compute such an optimal position for R on MA easily.
Still, long and narrow pockets and pockets with bottlenecks tend to result in a comparatively high variation of the step-over distance even if $R$ is distance-balanced. It may be better to split such pockets into sub-pockets, and to machine each sub-pocket individually. We use a penalty function to find split lines that subdivide the pocket into sub-pockets such that (a) the maximum variation of the step over within the resulting sub-pockets is minimized, (b) sharp corners at the split lines are avoided, and (c) the number of sub-pockets is kept small (or within user-specified bounds). Experiments were used to obtain default weights for the penalty function but these pre-specified weights can, of course, be overridden by a user.

Fig. 1: Sample runs of our algorithm on two pockets: (a) one spiral path computed according to [2]; (b) one spiral path with optimized start; (c) two spiral paths with optimized starts for a decomposition of the pocket; (d) optimized spiral paths for a decomposition of a pocket with islands. The dotted black curves represent the final pass along the input contours.

Discussion
We implemented our spiral machining algorithm in C++, based on the Voronoi package “VRONI” [3] for computing the medial axis of the pocket contours, and compared our new spiral tool paths to those of our prior work [4]. See Fig. 1 for a sample pocket, machined with one spiral path and two different start points, and alternatively split up into two sub-pockets that can be machined more efficiently. The tool path in Fig. 1(b) reduces the path length to 64% of the length of the path depicted in Fig. 1(a) and the number of laps from 30 to 20. The sum of the tool path lengths in Fig. 1(c) is only 63% of the length of the tool path in Fig. 1(b). Furthermore, the variation in the step-over distance is reduced. We extended our algorithm to pockets with islands by using the Voronoi diagram to compute appropriate links to connect the island contours with the outer boundary, see Fig. 1(d). Our experiments provided clear evidence that our algorithm reduces the overall tool-path length and avoids excessive variations of the tool-path curvature, the engagement angle and of the step-over distance.

References
Extended Abstract S2

Title
It is time to drop the “R” from NURBS

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Keywords
Biologically-inspired systems, NURBS, knowledge engineering, circle approximation.

Introduction
During the early eighties an important event took place: NURBS became an IGES standard paving the way for the CAD/CAM industry to adopt rational B-splines as their de facto representation for shape. The initial thinking was that a unified scheme was necessary to represent both conventional objects as well as free-form geometry, and NURBS fit the bill, at least this is what most of us early developers believed. Tons of research, both within academia and industry, was done and a text/reference book was written. As we dug our heads into the details and more and more capabilities were developed, strange phenomena were discovered. There were lots of problems related to parametrization, weights and the knot vector associated with the circle. It turned out that representing the circle as a rational spline had a very high price!

It is now clear from at least two decades of experience that the rational form, as flexible as it may be, is difficult to work with and if not used properly, can produce unwanted outcomes. Besides the above problems, it is evident that the rational form is far more complicated than its non-rational counterpart; it is expensive to compute, the weights are difficult to adjust and if used for circle representation, then neither the parametrization nor the continuity are desired. We argue that the time has come to remove the rational forms from our arsenal of shape mathematics and replace all required rational entities (conic sections) with approximations. We have enough experience to do just that and the hardware and software configurations support this effort perfectly well.

Biologically-inspired computing
Ever since the advent of computers in engineering design, computing has been number crunching, i.e. numerical data is passed on to the algorithm, it does a lot of computations and returns the result(s) or an error message that indicates something is wrong or cannot compute. While there are many problems with this kind of machine, the issue we want to focus on is repeated computations. Let us illustrate the problem using the circle approximation example. The algorithm would work as follows:

- Check if the input data is valid.
- Compute some number of sampling points and interpolate through those points with integral B-splines.
- Check the error on each segment using an iterative method.
- If the error condition is not satisfied, increase the number of sampling points, re-interpolate and recheck the error.
- The job is done when the algorithm has found the optimum number of sampling points and the error is below the given tolerance on each segment.

The problem with this algorithm is that every time the same (or similar) circle needs to be computed, all the steps have to be performed. That is, if we want to re-compute the circle, the optimization and the error checking part have to be repeated. This is like a human that never learns how to use a CAD/CAM system; every time a construction technique needs to be executed, he would look up the manual on how to do it.

Biologically inspired systems try to mimic the process of human creativity over time. Broadly speaking, there are four categories of knowledge:

1. I have done this before: the task has been done before and it is a matter of repeating the known steps.
2. I know how to do it: the task has not been done before, however, based on experience and on seeing how others have completed the same task, the operator knows how to do it.
3. **I think I know how to do it**: the task is not familiar but based on prior experience and research the operator may be able to complete the task.

4. **I have no clue of how to do it**: the operator is in foreign territory and it may take a long time to complete the task that may never happen.

In this work we rely on the first and the second type of knowledge to design a new class of algorithm to approximate the circle as a non-rational B-spline curve. To this end we need to complete the following tasks:

- To write a (set of) algorithm(s) whose only purpose is to experiment and to gain an insight into the intricacies of the numerical processes and the pitfalls of numerical methods.
- Store the experiences in a database for later use. This database should be expandable upon the availability of more knowledge.
- Write the required algorithm that does two things: (1) get information from the knowledge base to “know how to do it”, and (2) perform only the necessary computations without repeating what “has been done before.”

This approach represents a short-term pain and a long-term pleasure. On the short term we need to do a lot of experimentation, make lots of mistakes and record all this in a knowledge base. However, on the long term it will pay off handsomely as the circle will be computed accurately and very fast without repeating unnecessary steps.

**Circle approximation**

The circle approximation problem is formulated as follows. Given a circular arc with its center, radius, start and end angles, and a user-specified point coincidence tolerance, approximate the circular arc with a non-rational B-spline curve of given degree so that the following conditions are satisfied:

- the B-spline curve must not deviate from the circular arc anywhere along the arc more than the given tolerance;
- the parametrization of the approximating curve must be quasi-uniform, i.e. as close to uniform as possible; and
- the B-spline curve cannot have multiple internal knots or any other singularities.

For practical purposes we limit the available degrees to 2, 3, 4 and 5. For almost all design tasks degrees 2 and 3 are more than adequate, however, we allow the degree to go up to 5 because of the high degree circles that are in use by some CAD/CAM systems. Theoretically, there is no degree limitation, however, because we are building a method that is biologically inspired, for each degree one must build the necessary experience to “know how to do it.”

**Summary**

A knowledge-driven approach to circle approximation will be introduced in this presentation. There were two main motivating factors leading to the conclusion of this research: (1) decades of frustration with the rational form, and (2) the desire for a more intelligent computing environment that is similar to how humans learn and complete difficult tasks based on experience and creativity. To the first motivating factor we offer a superfast and nearly unbreakable method to approximate the circle with a non-rational form. In fact, we went one step further and proposed to drop the rational form altogether. Besides representing conic sections, there is no need for the rational form and since they can be adequately represented via approximation the “R” can be safely eliminated from NURBS.

To the second motivating factor we offered a new knowledge-driven computing paradigm that is based on experience building (learning), knowledge creation and a new form of algorithm design that omits elements of the algorithm that are unnecessary because “they have been done before” and we already “know how to do it.” Dumb computing, based on number crunching and error prone numerical iterations, has no place in the arsenal of modern engineering computing. The good news is that most computations can be replaced by knowledge-driven techniques, the bad news is that there is a learning curve, i.e. each algorithm has its own learning curve and a time factor to maturity. However, just like us humans, the older we get the more efficient we get, algorithms should improve in efficiency and robustness over time. That is, instead of hopelessly adjusting tolerances and patching up numerical algorithm, we argue that the way to go is knowledge building to empower algorithm with intelligent choices.
Extended Abstract 53

Title
On the use of machine learning to defeature CAD models for simulation model preparation

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Keywords
CAD model adaptation, simulation, machine learning, decision making, knowledge capitalization

Introduction
In the field of artificial intelligence, machine learning [2] techniques aim at identifying complex relationships characterizing the mechanisms that generate a set of outputs from a set of inputs. In the field of numerical simulation, the adaptation and idealization of CAD models can be seen as a succession of complex tasks involving many high-level operations whose parameterization relies on a deep knowledge and expertise not always clearly formalized. Thus, machine learning techniques can be a good mean to find rules that drive the CAD models preparation processes and capitalize the knowledge embedded in a set of adaption scenarios.

Depending on the objective of the targeted simulation (dynamic/thermal/heat transfer simulations, assembly/disassembly procedure evaluations, large-scale visualization, real-time manipulations for Virtual Reality applications and so on), as well as on the type of method adopted for solving it (Finite Differences, Finite Elements Analysis and so on), there exists a huge amount of possible treatments whose chaining strongly affects the processing time as well as the resulting accuracy of the simulation solutions. Among the others, the CAD model defeaturing is a crucial step which aims at removing irrelevant features. If those suppressions are not supposed to strongly affect the simulation results, they can however strongly speed up the overall simulation process. Thus, for a new simulation, it is important, not only to find the appropriate adaptation scenario, but also it is crucial to be able to identify the impact on the performance of the overall process.

This paper addresses the way machine learning techniques [3] can be used for understanding how to choose the candidate features for the defeaturing steps. Here, the difficulties concern the definition of the right data models to be given as inputs and outputs of the learning techniques. For example, the type of feature, its volume compared to the overall volume of a part, the relative distances between the feature and the loads are so many variables. Therefore, among the possible, it is important to identify those meaningful parameters as well as the thresholds that drive the engineers during the decision process. In this paper, a framework is set up and different scenarios are foreseen and analyzed.

Main Idea
Importance of the work and related state of the art. For a given CAD model and a given simulation objective, there exists several treatments (detail removal, part/product removal, fusion, shape simplification, size reduction, meshing, adaptation of meshing) that can be used in a different order to adapt the CAD model and prepare the simulation model [1, 4]. The choice of the treatments depends on a large number of variables and constraints relative to: the input data (e.g. characteristics of the CAD model, industrial constraints, needs of the designer, objectives of the simulation), the output data (e.g. targeted accuracy, cost/rapidity of the preparation) and intermediate parameters (e.g. available tools, setting parameters and cost of operations) which must be as exhaustive as possible. Today, it is therefore difficult to prepare a simulation model while really optimizing the preparation steps. In addition, those high-level preparations steps rely on a deep knowledge and strong expertise not always clearly formalized and thus difficulty automatable. At the end, and since a lot of time is lost on those preparation steps, very few time is dedicated to the simulation and the performance saying.

Approach and methods used in problem solving. The proposed approach is shown on figure 1. As a summary, the idea is to first model the treatment processes and identify scenarios (phase 1) to be able to find rules and thresholds that select a process and estimate its cost and performance (phase 2). Finally, those rules can be applied on unknown data (phase 3) that can also be taken into to further improve the rules and thresholds (phase 4).

More precisely, in the first phase, the initial database includes a significant number of already known configurations and scenarios. These scenarios contain all the above mentioned inputs, outputs and intermediate relevant variables. Some data may be automatically collected, others will be provided by designers. At this level, since the learning tool can also be used to select those which are significant to match the outcomes. Then, in the second phase, machine learning tools are used to find the rules.
and thresholds characterizing the mechanisms that have been used to find outputs from a set of inputs. The choice of necessary variables, the repeatability and robustness of the proposed algorithms are studied by selecting models in a series of cross-validation tests. The algorithm that best meets specifications is selected. In the third phase, those identified rules and thresholds can be applied on a new case (inputs known but output unknown). Finally, in a fourth phase the new output and input can then be used to consolidate the rules and adjust thresholds. Thus, the database is enhanced with theses new values.

![Fig. 1. Machine learning based approach to defeaturing CAD models for simulation model preparation](image)

**Achievements and validation of the results.** Among all the simulation objectives, this paper focuses on the heat transfer and stress analyses. Similarly, among all the above mentioned operations, this paper addresses the defeaturing of CAD models. To implement the proposed framework (Fig. 1), the Weka platform [5] is plugged to a VBA macro developed within CATIA V5. The output data generated by decision trees consist in a list of details to remove and treatments to use. Before that, machine learning tools were used to estimate the performance: feasibility of the simulation, the accuracy of the simulation results and the computation time (treatment and simulation times) of the removal operations. The considered input data can be tagged as belonging to a set (e.g. type of part, detail family) or as a dimensionless numerical value (e.g. ratio detail volume/part volume). For this, values were estimated from rules using data mining (recognition of the type of detail) and statistical analyzes (number of triangles, area and volume of the simplified model).

**Conclusion**

In this paper, the way machine learning can be used to learn how to defeature CAD models for simulation models preparation is investigated. A dedicated framework has been set up. It combines several models and tools used to support the extraction of data from initial and simplified CAD models, the inputs from the experts, as well as the learning mechanisms properly saying. The results are promising and prove that the machine learning techniques can be good means to capitalize the knowledge embedded in empirical processes like the defeaturing steps. In the future, such a framework should be extended to support all the other model preparation steps. At the end, the proposed approach and tools should reduce significantly the number and duration of design iterations, thus improving the product development cycles and increase the reliability of the design processes.

**References**


International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
Extended Abstract 54

Title
A potential field approach for collision avoidance in 5-axis milling

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Keywords
5-axis machining, Collision detection, Potential field, tool paths optimization

Introduction
5-axis surface machining is an essential process in the field of aerospace, molds and dies industries. 5-axis milling is required for the realization of difficult parts such as blades and impellers and is also very convenient to improve quality for the machining of deep molds in plastic injection and casting by reducing tool length. Despite the evolution of CAM software, 5-axis tool path programming requires advanced skills and collision detection remains a challenge during the tool path computation. One can distinguish two kinds of tool collision when addressing machining issues. The first one is local and only involves the active part of the tool, the second one is global and in that case the whole body of the tool, the tool holder and even the spindle can be considered.

Literature shows that collisions are often avoided using a geometric point of view. Indeed, the study traditionally starts with a representation of the tool geometry [1][2], then by a geometrical representation of the environment [3][4], thirdly by a collision test between the obstacle and the tool [5][6] and finally by a correction and optimization of the tool axis direction to avoid the obstacle [7]. In the field of robotics, other methods based on potential fields virtually attached to the obstacle are developed. These fields emit a repulsive force on the robot when it enters the neighborhood of the obstacle [8][9]. The aim of this paper is to show the benefit of using potential fields in order to prevent collisions during the computation of the tool axis orientation along a given tool path followed by the center of a ball-end milling tool.

Main idea
In the proposed approach, 5-axis collision avoidance is managed thanks to repulsive forces deriving from a potential field. The tool is considered as a rigid body moving in 3D space on which repulsive and attractive forces are acting. Repulsive forces are due to potential fields attached to check surfaces and an attractive force exerted by a spring is introduced to restore the tool axis orientation in the programmed configuration. Moreover, a viscous damper is used to allow the system returns to steady state without oscillating. The tool center follows the programmed path on the part surface whereas the tool axis orientation is modified to avoid the obstacle by resolving the fundamental principle of dynamics. Differential equations of the tool motion are solved using an Ordinary Differential Equation solver (ODE).

The repulsive force comes from robotics [9] and is formulated as follows:

\[
\begin{align*}
\vec{F}_{rp} &= \eta \left( \frac{1}{r} - \frac{1}{r_0} \right) \frac{1}{r^2} \cdot \vec{r} \cdot \vec{grad}(r) \quad \text{for } r < r_0 \\
\vec{F}_{rp} &= \vec{0} \quad \text{for } r \geq r_0
\end{align*}
\]

with

\[ \eta: \text{Repulsive force coefficient} \]
\[ r: \text{Distance between obstacle and tool gravity center} \]
\[ r_0: \text{Programmed neighborhood for the obstacle} \]

Two different applications are proposed. First, a tool moving along a straight line enters successively two spherical potential fields created by two single points. The tool axis orientation is automatically modified to avoid the collision and go back to its programmed orientation as fast as possible with a smooth response. This first case allows tuning simulation parameters such as mass, spring constant and damping as well as tool velocity during simulation to avoid oscillations.

The second study deals with a 5-axis open pocket application such as impeller machining. Part surface and check surfaces are modeled as Bezier patches. The check surfaces are discretized and every point of the mesh is considered as a repulsive point.
The main purpose is to avoid oscillations by choosing an optimum mesh size and by programming the return in the initial orientation with a critical or over damped behavior. Fig.1 and Fig.2 illustrate the results of both studied cases.

![Fig.1: Avoidance of 2 spheres neighborhood](image1)

![Fig.2: Avoidance of an Impeller-type surface](image2)

**Conclusions**

Research works introduced in this paper show an original method for 5-axis collision avoidance by using potential fields commonly used in robotics. Using potential fields allows to be sure that no collision will ever occur with the obstacles as the neighborhood emits a repulsive force growing to infinity when the tool gets closer to the obstacle. As the tool behaves like a damped harmonic oscillator, investigations are carried out to prevent the tool axis orientation from oscillating. Numerical investigations show that the proposed approach is efficient and perspectives brought by these works are numerous. In particular, the reduction of the tool length to minimize tool deflection and the smoothness of the tool axis orientation variation to ensure High Speed Machining are under investigations.

**References**


Extended Abstract 55

Title
FE analysis of contact between stump and socket during simulation of amputee motion

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Keywords
Prosthesis design, Socket-Stump contact, Human Modeling, Gait Simulation, and Finite Elements Analysis.

Introduction
The most important parameter to evaluate comfort of leg prosthesis is the contact pressure at the stump-socket interface. Experimental works have analyzed this parameter for typical postures and during walking of an amputee; but experimental tests require a real prototype of the socket equipped with transducer and this is not an approach that can be used in design process.

To face mentioned problem, we present, in this work, a virtual approach focused on design goals. The approach is based on a digital avatar of the patient, with lower limb prosthesis, and connects two different types of simulation, the first one concerning postures and gait, the second one the pressure evaluation with FE analyses.

The paper describes in detail the approach, the tools adopted and their integration and finally some case studies related to patients walking on flat or slop ground.

Main Idea
In modular prosthetics, the socket is the only custom fit part realized around the patient’s stump morphology, while components, such as foot, knee, and tube, are chosen from commercial catalogues according to patient’s characteristics. The socket represents the most critical component from which depends the whole prosthesis functionality. The key issue is the definition of its shape in order to reach the best comfort and fit. In particular, contact conditions between stump and socket change during amputee’s motion and virtual tools to evaluate these variable conditions can permit to achieve better design solutions.

We have integrated FE contact analysis with Human Modeling in order to analyze the pressure distribution on stump surface during different gait conditions. To achieve our purpose, we have integrated two main phases: first the gait analysis using the patient’s avatar (the case study is a unilateral transfemoral male amputee), then the FE contact analysis considering the loads distribution computed in the first phase.

The patient’s avatar is a customized instance of LifeMOD, a biomechanical modeling package based on MSC ADAMS system. A customized avatar of the patient has been implemented according to his anthropometric parameters; customized models of the stump and the prosthesis have been added to the previous described model (Fig. 1(a)). Patient walking has been simulated using motion laws deduced from experimental tests performed with Motion Capture equipment. The simulations permit to evaluate different configurations of the system stump-socket-prosthesis during walking and corresponding loads acting on the socket. Fig. 1(b) shows the screenshots of the Patient’s avatar during loading step in different stance phases (Initial Loading Response, Midstance, and Terminal Stance); while, Fig. 1(c) reports the three forces components and the magnitude over the phase from Initial Loading Response to Terminal Stance.

Fig. 1: Gait analysis model and results: (a) Patient’s avatar without and with stump and transfemoral prosthesis; (b) Patient’s avatar during (1) Initial Loading Response, (2) Midstance, and (3) Terminal Stance; and (c) Load components acting on the socket.

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10

Page 134 of 226
To analyze socket stump interaction we have used Abaqus software package and an automatic procedure based on the pre-processing knowledge representation by using Python language has been implemented. Model considered in FE contact analyses is just built on three parts having different mechanical behavior: bones, soft tissues and socket. Geometric models of bones and soft tissues were obtained by Magnetic Resonance Imaging while socket was modeled by using a software package, named Socket Modeling Assistant, specifically developed to model socket component. Geometric models are imported in .iges format: bony structure and soft tissues are considered as 3D solids and merged to form a single part, the stump, without geometric discontinuity; while the socket is modeled as shell. Mechanical properties of soft tissues of residual limb are modeled as linear, homogeneous and isotropic: values of 0.2 MPa for Young’s modulus and 0.3 for Poisson’s ratio were considered, according to models developed by Jia et al. [1, 2] and Lee at al.[3]. We considered the socket and the bony structures as rigid bodies because Young’s modulus of these two parts is five orders of magnitude greater than soft tissue ones and also to reduce computational time [4]. Because of the automatic procedure, we adopted a free auto meshing technique and used explicit elements: 3-noded triangular (S3R) elements for the socket and 4-node tetrahedral (C3D4) for the stump.

We performed explicit simulations and considered three phases that correspond to the deformation stages of soft tissues. The first step replicates the donning of residual limb into the socket and imposes a pre-stress on the stump, as first reported by Zhang et al. [5]. Then, the adjustment step follows to reach a better repositioning of the socket around the stump and to obtain maximum comfort. In the third and final step, the loads achieved by gait analysis are applied to the centre of mass of the socket. Donning and adjustment steps are friction-free, while during loading the friction coefficient is equal to 0.46, as adopted by Zhang and Mak [6].

Fig. 2. shows a brief comparison of pressure distribution outcome during loading step in three different stance phases.

Fig. 2: Pressure distribution on stump surface during loading step in different stance phases: (a)(d) Initial Loading Response, (b)(e) Midstance, and (c)(f) Terminal Stance.

Conclusions
In this work, we propose an embedded and automated approach to simulate the interaction between socket-stump in transtibial prosthesis, demonstrating its feasibility. Furthermore, by integrating FE model on patient’s Avatar and performing a gait analysis, it is possible to determine the pressures distribution on the stump at any time of the stance phase during amputee’s walking.

Simulation results offer precious information to characterize the pressure distribution on the stump under different deambulation conditions and improve quality and comfort of the prosthesis socket.
Acknowledgements
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Extended Abstract 56

Title
Mapping Design Rationale to Support Function-Behavior-Structure Modeling in Product Design

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Keywords
Design Rationale, Function-Behavior-Structure Modeling, FBS, Semantic Analysis, Text Processing

Introduction
Recently, as the increasing amount of textual design documents, such as design reports and patents, studies on design information management from textual data to aid design analysis for different design stages have been received much attention. In conceptual design, function-behavior-structure (FBS) modeling is one of the classical design methodologies in relation to function modeling [1]. Function, behavior and structure are widely accepted aspects of design information for design synthesis. Although textual design documents contain relevant information, the narrative structures have made the process of identification and extraction of functional related information a challenging task.

In our previous study, we have explored text mining approaches to discover design rationale (DR) from archival design documents. DR information is helpful to assist designers in understanding design. However, it is inadequate and not intuitive for FBS designers who would like to search from aspects like function and behavior while these aspects of information may not be explicit in most of DR models. In order to assist function modeling, we propose a semantic-based mapping approach to extract and transfer DR information into FBS representation. This process will help to suggest possible functions concerned by designers, relevant behaviors used for designs and identify component relations.

Main Idea
In order to formulize the information mapping from DR information into FBS, a conceptual analysis is first conducted to understand the semantic relations between representation elements in both DR representation and FBS models.

The proposed ISAL model represents DR information from three layers, including issues, solutions and artifacts, and their relationships [2]. Issue layer represents the design motivational reasons and objectives of an artifact. It includes sentences which describe the motivations, shortcomings or challenges for a design. Design solution layer represents how the motivations can be addressed and fulfilled. It is often described by sentences that elaborate methods and their reasons concerned. Artifact layer refers to objects resulting from human activity. It is usually represented by single words or phrases that describe components, features or properties of a product.

Several functional models are reported in literature from different researchers’ perspectives. In this study, a mapping process is designed in order to help designers to identify and retrieve design information from FBS aspects. Based on this objective, FBS representation in this study is viewed from a broad sense. In general, functional features refer to the motivations/purposes of a design [3]. It should represent the intended effect of a system. Behavior is related to what the design does to fulfill the function. Structure describes the components of the design and how they relate to each other [4].

![ISAL Model Diagram](image)

Fig. 1: The example of relations between ISAL model and FBS.
Based on the analysis of elements in FBS and ISAL, we can find the connections between these two representations. The content in issue layer and reasons of methods presented in the solution layer are close to the content of functions. Behavior can be identified from methods about the process used to achieve the function from the issue and solution layers. In addition, the structure aspect of FBS can be identified from artifact layer of ISAL. Fig. 1 shows an example of relations between ISAL and FBS. In general, functions often refer to verb phrases and noun phrases, e.g., “lower the material cost” and “create a greater likelihood of crosstalk”. Behaviors are usually described by verb phrases, noun phrases and preposition phrases, e.g., “drop the ink”, “ink release” and “by making the substrate smaller”. Based on the component information, relations between components can be discovered using phrase relations at sentence level, so as to form a hierarchical structure of a design.

Based on the analysis and observations of language patterns in DR, the basic idea of this framework is to discover language units, e.g., words or phrases, associated with function, behavior and structure aspects from DR information. The proposed approach explores natural language processing and machine learning techniques. Fig. 2 shows the proposed framework for mapping DR information based on ISAL model into FBS representation.

Fig. 2: The proposed framework for mapping DR information into FBS model.

The proposed framework includes four major processes. Firstly, given a textual design document, the proposed computational approach is adopted to discover and extract DR information based on the ISAL model [5]. Next, for modeling the structure of FBS model, a statistic-based approach is proposed to analyze the relations between artifact information. Thirdly, a linguistic feature-based method is introduced to extract candidate language units for function and behavior identification. Based on the local and global features in the context, a sequential labeling approach is designed to tag the candidate units with function and behavior.

In order to demonstrate how the proposed approach works, a case study using patent documents related to inkjet printer as the research data is provided. Firstly, given a patent document as input, based on the DR modeling process, the most representative language units including sentences and terms are selected as DR information based on ISAL model. Then the element labeling process provides a possible way to eliminate the irrelevant elements to retain information about functions and behaviors. Finally, using the structure modeling from textual data, an example of how closely components are connected is illustrated. The case study shows that the proposed semantic-based mapping approach is able to extract and suggest possible functions, relevant behaviors and component structures from DR information.

Conclusions

In this paper, a semantic-based mapping approach is proposed to transfer DR information into viewpoints related to function, behavior and structure to facilitate FBS modeling for product design. The case study shows an example of how elements related to FBS can be extracted and mapped from DR. By using those extracted elements as index units, it can help to locate and search design information from patents in function, behavior and structure aspects.

References

Extended Abstract 57

Title
Interactive interior design in Augmented Reality environment

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Keywords
Augmented Reality, Interior Design, Virtual Prototyping.

Introduction
Up to date, designers (including product designers, interior designers, ...) use commercial tools to represent, develop and evaluate design solutions. In particular, during the evaluation phase, they need specific tools to present their design solutions to the company or to the final users. Traditional tools are mainly used to produce bi-dimensional representations, such as technical drawings and photorealistic renderings. However, in order to show the actual characteristics of a designed solution, it is necessary, very often, to introduce the usage of real prototypes. Since making real prototypes is an expensive and time-consuming activity, and bi-dimensional representations are not very descriptive, other tools based on Virtual Reality (VR) and, more recently, on Augmented Reality (AR) technologies have been developed to support the evaluation phase [5]. One of the major benefits of using VR and AR tools is the higher users’ involvement during the evaluation activities in comparison to the traditional bi-dimensional representations. Besides, if these evaluation tools are compared with the development of real prototypes, we can state that they allow saving design development costs and time, and that they give the possibility of performing a better product evaluation during the whole design process. AR, in particular, allows the user to see these digital prototypes in the real world [1] by maintaining temporal and spatial coherency between digital and real elements. Consequently, the evaluation activities become even more effective, since the designer is able to see the design solutions directly in the real environment. The research activities presented in this paper aimed at developing a designer-oriented, transportable and cost-effective AR system and demonstrating, through a case study and tests with users, its effectiveness as support for the current interior design practice. This paper presents the technological features of the AR system (architecture, main components, etc.), a real case study in the field of interior design and a testing session with junior interior designers. In particular, the research focuses on the Contract Design sector, in which interior designers are in charge of designing interior spaces considered as “standard”, repeatable many times (such as, in case of hotel rooms) in different places (as for instance, in case of stores) and to be used and enjoyed by many final users.

Main idea
The AR system described in this paper has been developed on the basis of a particular tracking system that is able to extend the working space of the AR marker-based tracking [3]. The AR system integrates the marker-based tracking with the tracking ability of a robot. A fiducial marker has been placed on the robot that co-works with the user to maintain the marker always traceable. Consequently, starting from an absolute reference point, the AR System is always able to track its position in the space even if the robot moves within the environment. This approach allows tracking a wide working area by using only two markers, instead of using a standard multi-marker solution [2].

Besides the tracking, the system provides several interaction modalities to manage 3D models within the AR working area. Mainly, the application gives the possibility to choose a model from a database and change its position and orientation according to the absolute reference system. Thanks to this feature, the arranging and re-arranging of virtual furniture or other virtual objects become a simple task, which can be carried out also by people not skilled in AR applications. Several design solutions can be arranged, stored and then shared and evaluated with other people, as final users, buyers and so on, in order to achieve the optimal and desired arrangement.

The AR system has been evaluated and validated by means of experimental tests in a real case study. The target users of the AR system are interior designers, who can use the AR system in their daily design practice. The case study has concerned the design process for developing a Serviced Apartment (SA) to be used as a “standard model” in the context of a project for the Contract Design sector. Specifically, the goal of the use of this AR system and application in this specific design contest is to reduce the costs associated with the evaluation phase: in this particular design context, in fact, this activity is usually carried out by using real “prototypes” of the developed design solutions, which are real apartments equipped with real furniture [4]. On the contrary, by
using the proposed AR system, designers can present and evaluate with the buyer and the final users several design solutions, which can be modified in real time at no additional cost, and only afterwards make a real final prototype. In order to carry out an experimental case study, as closer as possible to the real design practice, has been defined following the course of a traditionally design process. The results of the case study have been used to verify the actual integration of the proposed AR system in the common interior design practice.

Then, starting from the buyer’s requests and inputs, a design team -made up of two senior interior designers- has carried out the following activities:

1. defining the target users of the SA and their possible needs;
2. defining the spatial layout of a single SA;
3. identifying the furniture with which to equip the SA;
4. developing 3D models, by using commercial 3D software, of the SA and of the furniture (if not available from their brand);
5. processing the 3D models in a file format compatible with the AR application;
6. using the AR system for developing several design solutions, arranging the selected furniture in different layouts or using different materials and colours, and their storage.

During the case study, quantitative data concerning the design activities related to the use of the AR application and system (e.g. the time for the processing of the 3D models of the furniture) have been collected by the authors. Also, at the end of the abovementioned activities, the authors collected some remarks from the interior designers involved in the project.

Finally, the authors conducted a testing session with some interior designers, who were not involved in the case study and were not skilled in the use of AR technology. The testing session has concerned the use of the AR system for arranging pieces of furniture starting from the design solution already defined in the case study. The testing session involved more users and the results have been used to evaluate the overall usability of the system and, in particular, the easiness and the time of the learning activity necessary to properly use the system.

Both the case study and the testing session have been used to assess the level of satisfaction of the target users (interior designers unskilled in the use of the AR technology) about the AR system compared with the tools traditionally used for presenting the design solutions to the buyers (photorealistic renderings, technical drawings, etc.).

Conclusions

The analysis of the collected data, which are extensively presented in the paper, demonstrated that the innovative AR system and application can be effectively used and integrated in the design process and can constitute an important competitive advantage for designers who will use it for developing design solutions and present them to and evaluate them with buyers and final users. The main features of the AR system, developed with a user-oriented approach, have led to a high level of appreciation concerning the intuitiveness and easiness-to-use of the AR system and its interface, short time necessary for learning the AR system main features, a high level of appreciation of the immersiveness obtained by the use of the AR system for representing the developed design solutions and a high interest in the possibility of introducing the AR system in their design and evaluation activities. Also, interior designers expressed some remarks about the possibility of automatically identifying and hooking sensitive points of the virtual environment and furniture, and to integrate in the augmented environment dynamic shadows of the pieces of furniture. In addition, measurement tools will be implemented to allow users to objectively evaluate distances and dimensions during the furniture arrangement. The authors of this work consider these remarks as the starting point for carrying out further experimental research activities.

References

Extended Abstract 59

Title
Integration Of Machining Constraints In Design Optimization Of A Guide Vane Cascade

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Keywords
Blade Design, Geometrical Optimization, Flank Milling, Meshing Strategy, Machining Constraints

Introduction
In hydraulic turbomachinery, design optimization of blades to improve performances is an important issue. The conventional blade design and production process could be described in three steps. First, a Computer-Aided Design (CAD) modeling is done based on Computational Fluid Dynamics (CFD) simulations. Then, the tool path is computed, using Computer-Aided Manufacturing (CAM) software. Finally, blades are machined on 3 or 5-axis machine tool. The expected hydraulic performances are computed using zero defect CAD models and software [2]. On another hand, blade functional surfaces are made of freeform surfaces, obtained by high added value machining operations, like 5-axis milling. As machining constraints are not taken into account in the design step, difficulties come in the tool path computation and tool path interpolation [5] and, in the end, hydraulic performances are not those expected.

In this paper, a new approach is proposed to design hydraulic blades based on machining considerations and applied to guide vane design.

Main Idea
In order to avoid geometrical deviations between machined blades and the CAD model, the proposed approach consists in taking into account machining constraints at a very early stage in the CAD modeling. In the proposed paradigm, the machining tool path is placed on the heart of the design process [1]. The polynomial machining tool path is computed so that the machined blade, not the CAD model, is optimum with respect to the hydraulic performances. Then, the optimization validates the surface geometry resulting from a machining simulation (Z-buffer simulation) and CAD model is the 3D representation of this simulation. Manufacturing is easier, faster, geometric quality and perceived quality are improved and hydraulic performance should meet expectations.

The proposed work focuses on the comparison between the standard optimization process, called “Design”, and the proposed approach called “Toolpath” based on the polynomial description of the tool trajectory using flank milling. Those two methods will be developed on a 2D study case: the geometric optimization of a guide vane cascade, one of the turbine parts which convert hydraulic power to electric power. The purpose of this article is to find out if performances obtained with a classic optimization (Design) and with machining constraints based optimization (Toolpath) are comparable.

The optimization process used here can be decomposed in four stages. The first stage consists in defining a parametric model of the guide vane (Design model) or of the tool trajectory during milling (Toolpath model), e.g. Fig. 1.

Fig. 1: Design and Toolpath models
In order to describe a blade geometry, several researches have been looking for coherent methods [3]. The choice made here is to describe the planar geometry of a blade by a camber line, a suction side and a pressure side. Those three curves are modeled with B-spline curves. In the Toolpath model, it is the tool center trajectory which is described; then, the blade geometry is deduced using a discrete inverted offset method. Machining constraints like continuity or curve order are introduced to only describe geometries, which can be machined on a standard numerical controller. The difficulty is to determine how many parameters are needed to lead to a correct model, knowing that with an important number of parameters, more complex geometries can be described. On another hand, the optimization stage is longer, because of the bigger number of input parameters.

The next step is to define a computation domain and to develop a meshing strategy. As we are in an optimization process, a lot of computation are needed, each one with a different set of parameters. The point here is to develop and to refine a script which can automatically mesh all the geometries created and build a computational domain smaller as possible. Indeed, smaller the domain is, faster the computations are. So, the script has to adapt the mesh with the different values of the parameters and to use symmetries to reduce the domain. It leads to the definition of the “Inter Blade Channel”, which is the smaller domain possible to describe the entire guide vane cascade geometry (topology and mesh for this channel are described on Fig. 2). To control efficiently the mesh, structured mesh strategy is used.

![Fig. 2: Inter Blade Channel structured topology and mesh](image)

The third step is to run CFD simulation on the mesh created to determine the guide vane cascade hydraulic characteristics. Values such as “Angular Momentum” (AM, which is helpful to define hydraulic power) or “Head Losses” (HL, which helps to estimate energy losses in the guide vane cascade) are computed. A study on the computation convergence is done here to find out if mesh quality is great enough during numerical simulations.

Finally, the last step is to find the optimal geometry. We want to find the geometry which leads to a given value of AM, with a minimal value of HL. Two methods are used, parameterized and compared here: Genetics Algorithms (GA) and Kriging [4]. GAs give good results, but computational times rise to unacceptable values when the number of parameters becomes too high. This is why Kriging is envisaged. This interpolation method needs fewer computations than GAs for a high number of input parameters, and leads to great results when it is correctly done.

**Conclusions**

In the end, this study shows that Design and Toolpath models lead to similar optimal solutions in terms of hydraulic performances. Moreover, with our approach based on machining constraints integration in design process, CAD models of blades match in a better way with machined blades. Taking into account of the results obtained here, a study based on the same principle will be done with 3D geometries, considering blades with non-developable surfaces, like hydraulic runner.

**References**


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Extended Abstract 60

Title:
Streamlining Function-oriented Development by Consistent Integration of Automotive Function Architectures with CAD Models

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Keywords
Function-oriented Development, Virtual Technologies, Virtual Prototyping, Systems Engineering, Digital Mock-Up

Introduction
Today, the rising complexity of modern cars is one of the primary challenges in the automotive industry [1],[4]. One significant complexity driver is the high amount of vehicle electronics respectively vehicle functions, like Park Assist, Dynamic Light Assist or Start-Stop Automatic. Such functions are implemented as complex, mechatronic systems, consisting of sensors, actuators and controllers. A function-oriented approach to development addresses the interdisciplinary implementation of such systems. This approach complements a component-driven development by extending the overall focus on functions rather than single components and is a fundamental requirement to handle the rising complexity in automotive development [1],[3],[5].

Virtual technologies are computer-based methods for the processing of virtual product prototypes and provide an important resource in the automotive product lifecycle management [2],[6]. A typical field of application is a digital mock-up (DMU), which describes the utilization of CAD models for geometric analyses. At this stage, however, the capabilities of virtual technologies are not yet fully exploited for a function-oriented development because function-oriented data structures are not yet integrated with geometric CAD data.

Main Idea
Our research focuses on the interdisciplinary integration of automotive function architectures with CAD models to exploit synergies and to enable new, beneficial methods for the spatial visualization and utilization of such data (see Fig. 1). In the following, we use the term function data as a short description for such function architectures. Our main contributions begin with an analysis of relevant data structures, systems and processes. Moreover, we develop a meta-format for the system-independent description of function data and we discuss and define requirements for a consistent data mapping. In addition, we carry out a prototypical implementation by which we derive new methods for the processing of function data. Finally, we evaluate these methods by means of actual use cases.

![CAD Data Integration](image)

**Fig. 1**: Our approach integrates function architecture data with CAD data.

We use the Siemens Teamcenter data management system that enables an export of CAD data with two complementary file formats: JT (Jupiter) and Siemens PLM XML. Hereby, the geometric data is kept in the JT file while structural information and product attributes of the CAD data are separately stored in the PLM XML file. The PLM XML format enables an integration of custom meta-data into a set of CAD data while ensuring compatibility with established system standards and processes. The function data is an architectural description of a mechatronic system consisting of different elements which include components (sensors, actuators and controllers), connections and properties of these elements. We developed an XML-based format for the description of function data that exploits the advantages of XML, including interoperability, human-readability and data...
validation using schemas. An important advantage of our format is that it allows for integration of function-oriented data structures into PLM XML structures. Moreover, it enables an interdisciplinary exchange and utilization of function data across different systems and domains. The latter provides a significant contribution in mastering the increased complexity in a function-oriented development. In addition, our work defines requirements for a consistent data mapping so that elements of the function data can be explicitly assigned to geometric parts of the CAD data by the use of clearly defined key fields.

We carried out a prototypical implementation using an established visualization system to explore the capabilities of our data integration concept. Based upon this prototype, we derived new methods for the spatial visualization, analysis and visual communication of function data. For instance, our methods include visualization of function-related components and wires in a virtual car model as well as visual reports based on specific system properties. Fig. 2 shows a visualization created with our prototype that highlights the system assembly of the car function Headlamp Flasher within a VW Golf 7.

![Prototype Diagram](image)

**Fig. 2:** Function-oriented visualization of the car function Headlamp Flasher in a VW Golf 7. Function components are highlighted in colors depending on their type and function-related wires are marked red within the electrical system (blue).

Our novel approach at consistent data integration allows engineers to have a simultaneous and consistent view on function-oriented and geometric data throughout development processes and the product lifecycle. Examples of use cases are functional data presentations, documentations and visual communication of functional relationships. In addition, our approach enables spatial comparisons of function assemblies across specific vehicle projects. In the customer service, a spatial visualization can assist technicians to easily track specific components related to particular functions. Moreover, it enables reclusions about other functions that may be potentially malfunctioning because of their relationship to a defect component. Finally, our work provides fundamental data structures that are required for a functional mock-up which utilizes behavior models to enable functional simulation.

**Conclusions**

A holistic development process that integrates function-oriented development and geometric design is still a comparatively young concept. In our work we have shown that it is possible to implement the integration of function-oriented data with CAD data in existing development processes. We have demonstrated the importance and benefits of our approach with a few use cases. The concept of holistic and interdisciplinary development raises challenges at interfaces as well as at the mindsets of developers and our approach shows a lot of potentials for further exploitation.

**References**

Extended Abstract 61

Title
An integrated approach supporting design, simulation and production engineering of connection techniques in automotive body-in-white development

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Keywords
Body-in-white, connection techniques, CAD-CAE-CAM integration

Introduction
The development time of new vehicle models has been shortened rapidly in the recent years. This is possible mainly due to the continuous integration of virtual development methods 0, 0. Today’s automotive industry is determined by ever shorter development times and an increasing accuracy of data quality already in early design phases. This reduced development time leads to new challenges in terms of virtual processing 0. The achievement of continuously shortened development phases succeed especially by an increased integration of parametric design 0. Furthermore, the implementation of 3D-CAD methods in nearly every section of automotive engineering leads to a significantly increase of development process efficiency 0.

Besides the general workflow in automotive body-in-white design, these facts also influence the development of connection techniques in automotive engineering. Due to the wide range of influencing factors, the concept phase of automotive body-in-white design requires a very high level of geometrical and functional detail from the virtual components. The main challenge is based on the transfer of metadata, which is not easy within geometry-oriented CAD environment, especially for joining pairings, which are particularly important in terms of positioning purposes. An efficient data transfer is necessary to achieve a satisfying representation quality of the desired pairings. Therefore, the use of metadata-based information is essential.

The great challenge is to establish a method, which is able to provide detailed information about the applied connection techniques from the beginning of conception until the final development cycles. In this way, the designed components can be verified and optimized in combination with different calculation and simulation processes. In the course of several optimization cycles, the engineers have to change the automotive body sheet geometry and have to provide the latest connection technology right in time for subsequent processes. Besides a close integration of design and simulation, a continuously information flow to production engineering is important.

Main Idea
An important task with respect to connection techniques in body-in-white design is the efficient creation of welding points within the CAD-system. Modern cars include up to 5000 spot welds and further weld lines, bold lines and rivets 0. In Fig. 1 a selection of spot welds on a body-in-white sheet is shown. The creation of these points can sometimes be a very involved process. For the representation of the joints in a digital mock-up (DMU) the representation of simple geometry points cannot fulfill the requirements of enhanced data processing. Besides a clear geometrical representation of different types of connecting techniques (e.g. 2-sheet weld spots, 3-sheet weld spots, weld seams), a direction vector for the welding process and additional information regarding spot weld diameter, materials, etc. have to be created.

Fig. 1: Exemplary spot welds on a body-in-white sheet metal part.
Another challenge arises from a lack of information transfer between different disciplines of development. The separation of geometry creation, finite-element based strength and durability simulation and production engineering leads to a challenges regarding an efficient data transfer by application of interfaces for the different computer programs. In the development process of a vehicle, the design of the concept starts within a CAD-environment. After that the general concept is verified within a computer-aided engineering (CAE)-system by application of different calculation and simulation methods, for example for crash and vehicle durability investigations. In correspondence with design and optimization, the production engineering is carried out by use of methods of computer-aided manufacturing (CAM). An essential aspect for efficient development is an effective transfer of geometry and functional information. The present publication presents a method which supports the creation of spot welds in automotive body-in-white development. The design process itself is supported by an automated creation of any desired number of spot welds on specified sheet metal components. A center curve is created by selecting a flange and the application of specific programmed automated geometry generation methods. On this center curve points are set by using an integrated algorithm. The number and the distances of the points can be determined in advance by the engineers. In the next automation step, the identified connection points are marked through lenses and the normal direction vector to the flange is set.

In case of weld or bond lines, the application automated generates points on the guide line in a predefined distance. These points are important to define the junction for subsequent calculation or simulation processes.

The aforementioned interface problems are solved by an additional application for repetitive processes. Else the metadata information transfer can be done by using implemented macros. The engineers are assisted in the creation of connection techniques and forced to a simultaneously integrated consistent process. This ensures that the processes are maintained throughout the entire development cycle. The respective input information is stored in each model by using an ordered parametric structure. This strictly predetermined structure can then be retrieved and transferred to a neutral data format and reused by any calculation, simulation of production engineering application. This continuous process is especially relevant in view of homogenization of specific optimization in the respective departments. This creation of a very homogeneous structure can be reflected for example in crash and fatigue strength with the later production. In addition the recirculation to the CAD-system with complete verification in terms of accessibility and joining sequences is possible. To enable these closed consistent cycle, this additional application has been designed in consideration of user acceptance and available information in different phases.

Conclusions
The introduction of a continuous process for the connection technique creation in automotive body-in-white development enables an enhancement of former separated CAD / CAE / CAM processes. This is achieved by use of a specific developed application that is implemented within the respective CAD-environment. This additional application further provides the possibility of the metadata information distribution, which is particularly relevant in relation to joining pairings. By using of automated routines, a continuous process is created, which is especially relevant to the homogenization of various departments. To close the loop and to integrate the evaluation, return cycle to the CAD-system is provided. The information transfer is accomplished by neutral data formats for geometry data and a specific text-based data format for functional information, which close the information transfer gaps between different types of CAD-, CAE- and CAM-systems.

References
Extended Abstract 62

Title
Solving under-constrained assembly problems incrementally using a kinematic method

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Keywords
Assembly constraint, assembly modeling, kinematic joint, constraint solver

Introduction
Assembly design plays an important role in product design activities, for most manufactured products are assemblies of individual parts. After part design, a designer constructs assembly models that contain information about the relative positions of parts, obtained by specifying assembly constraints between parts in a CAD system, which will solve those assembly constraints to find out the positions of parts.

Although geometric constraint solvers have succeeded in many 2D geometric problems, to efficiently and stably solve 3D geometric problems is still a challenging task. Some special approaches have been proposed to solving assembly problems. Generally, those methods can be classified into two categories: graph-decomposing method [2,4,5] and kinematic method [3,6]. A decomposing approach is vulnerable since it depends on the well-formed properties of a constraint graph. Also, since a subproblem has always multiple solutions and a constructive solver should be able to navigate the solution space to select appropriate ones to synthesize a solution of the total system, which normally requires the solver can enumerate all solutions of a subproblem, which is too expensive for an interactive CAD system. A kinematic method is to convert an assembly constraint problem into a constrained rigid multi-body system, which will be solved using the technology of inverse kinematics [1]. The advantage of a kinematic method over a decomposing method is that it can handle under-constrained closed-loop problems well and requires less numerical cost normally.

Main Idea
In a realistic interactive CAD assembly system, a designer starts the assembly step by step from scratch. The operations include bringing into or deleting from the assembly a part or mating condition, moving a part with respect to the constraints, etc. In most circumstances, the constraint graph is in the under-constrained state. All those operations could invoke necessary re-computation to reflect the changes to the constraint graph many times, and then it’s necessary to reduce the expensive computing as much as possible. We note that a typical product composed of many parts can be settled part by part sequentially, while only a few closed loops required to be solved simultaneously. To reduce unnecessary computation, we use the degree-of-freedom analysis geometrically to analyze the residual degrees of freedom between two parts and maintain such information for the next operations incrementally. When a change in the constraint graph occurs, we identify and solve the affected biconnected subgraph using cut-joint method, and spread out such changes only using rigid transformations. Also, a strategy is proposed to construct the joint reference frames from the initial positions, which makes the solver generally produce a result more close to the configuration of the assembly before changes occurred.

As depicted in Fig. 1, the graph $G$ can be decomposed into four biconnected components $G_1(v_0, v_1, v_2)$, $G_2(v_2, v_3, v_4, v_5)$, $G_3(v_2, v_6, v_7)$ and $G_4(v_5, v_8, v_9)$. Suppose $v_0$ is the fixed base. If the constraints represented by the edge $(v_1, v_2)$ are changed, the geometric satisfaction proceeds as follows: first we recalculate the subgraph $G_1$ to get its configuration. Then we solve the subgraph $G_2$ and $G_3$ independently. At last $G_4$ is re-solved. Noting that the adjacent biconnected components are connected by only one body, we can simplify the solving procedure by getting the configurations of $G_2$, $G_3$ and $G_4$ with a rigid transformation. This solving process is demonstrated in Fig. 2, where a tree structure is utilized to denote such propagating process.

When we start to solve the constraint system, to respect the user’s intent as much as possible, we define a new body reference frame and joint reference frame for the sake of solving. First, the new local reference frames of all bodies are settled down initially coincident to the global reference frame. Thus, those initial postures referred to the global frame are zeros and identical matrices. And the joint reference frames are created analytically from the initial positions according to such a rule: the
relative positions between two adjacent connected bodies should be as close to the initial positions while the value of the joint variables are zero. Such a strategy will benefit the numerical method since we can always start a numerical iteration from the zero initial estimates.

Conclusions
Experiments show that our presented incremental method reduces down the cost of solving an under-constrained assembly problem. By constructing the joint definition frames carefully from the initial positions, a solution close to the user’s intent can be achieved simply using a Newton-Rapshon method without requiring an optimization method.

References
Extended Abstract 64

Title
Domain Mapping for Volumetric Parameterization using Harmonic Functions

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Keywords
Volumetric parameterization, Harmonic functions, Streamlines, Shape centre

Introduction
If one can obtain any point of a 3D region with the help of a three unique bounded values/parameters then the region is said to be parameterized. For example, with the help of a radius and two angles, we can locate any point of a solid sphere. But, it is extremely difficult to develop a similar parameterization for a general/non-convex shape like, star fish (figure 2), human face etc. But such a continuous parameterization is necessary for many applications related morphing, texture mapping, shape matching and re-meshing, isogeometric analysis etc. Since such a parameterization involves parameterization of both boundary (which is a surface in 3D) and interior, it is called volume parameterization. Though several methods have been developed for parameterization of surfaces in 3D [1], not many methods are proposed for parameterization of the entire volume of a 3D model. Not even a few dozens of articles exist in the literature on volumetric parameterization. A mapping between two reference free-form models was established by using volumetric parameterization by Wang et al [2] while keeping the spatial relationship between the two models intact. Very recently, isogeometric analysis (IGA) has become an important area of application for volume mapping which may accelerate research in volume mapping. Martin et al [3] developed a technique for volume parameterization that can be used in IGA.

We use harmonic functions to establish a potential field across the domain. Then the streamlines are tracked using the potential gradient within the domain. Due to the property of the streamlines, they approach the shape center at unique angles. When combined with the computed potential of the internal points, the three parameters establish volumetric parameterization. Proposed approach for parameterization is analogous to a solution of heat transfer problem.

![Figure 1: A 2D domain with contours and streamlines.](image1)

![Figure 2: A star shaped domain](image2)

Domain Mapping and Heat Transfer Analogy
The objective is to obtain the required unique values for parameterization by solving a heat transfer problem in the given region. Figure 2 shows the heat flow-lines/streamlines (blue) and the isothermal contours for a 2D non-convex shape. A constant temperature heat sink is located at the shape center and the boundary is maintained at a constant elevated temperature. Under these conditions, a temperature gradient is set up between the boundary and the heat sink at the shape center, which decreases as the boundary is approached. It should be noted that the lines emanating from the boundary and approaching the shape center (streamlines) never intersect each other and approach the shape center at a unique angle. This angle value is assigned to all the
points of a streamline (i.e. angle value is constant along a streamline), while the temperature decreases from the boundary to the shape center along a streamline. Thus, we have two parameters (temperature of a point and the angle subtended by the streamline at the center) which can be used to locate any point within the domain. The above analogy can be extended to any non-convex domain in three dimensions. The only difference being that, in three dimensions, a pair of angles (polar and azimuthal) is required to completely define the angle of approach. Therefore, the two angles along with the temperature value parameterize a 3D domain. Identifying this fact that solving a boundary value problem (BVP) to establish a potential field over the domain directly helps in parameterizing the given domain we use harmonic functions to establish the required field. Solution of the BVP involves following five steps.

i. Discretization: A 3D grid is constructed using the input data points. The grid points are classified as exterior/boundary/interior based on the neighborhood information. A point within the domain is chosen as the shape center so that it is reachable from all boundary points as easily as possible.

ii. Boundary Conditions: After the data is discretized, Dirichlet boundary conditions are applied for the boundary and shape center i.e. a potential value ($\phi$) of 1 is assigned to all the boundary nodes and 0 to the shape center. All other interior points are assigned a random potential values between 0 and 1 as initial values.

iii. Potential Computation: To determine the temperature value at the interior points, Laplace’s equations is solved using the iterative finite difference method. An expression for the potential at a point ($x_i,y_i$) can be derived by keeping the step sizes same in all direction and substituting for numerical derivatives in Laplace equation. If the potential value at a point ($x_i,y_i$) in $j$-th iteration is $\phi_j(x_i,y_i)$, in the $(j+1)$-th iteration it is given by

$$\phi_{j+1}(x_i,y_i,z) = \phi_{j+1}(x_{i+1},y_{i+1},z) + \phi_{j+1}(x_{i-1},y_{i+1},z) + \phi_{j+1}(x_{i+1},y_{i-1},z) + \phi_{j+1}(x_{i-1},y_{i-1},z) + \phi_{j+1}(x_{i+1},y_i,z) + \phi_{j+1}(x_{i-1},y_i,z)$$

The termination criterion is given by $\max|\phi_{j+1} - \phi_j| \leq \epsilon$ where $\epsilon$ is the tolerance limit. A wise choice of $\epsilon$ is important. A very small value will increase the accuracy of potential computation, thus enabling good streamline tracking, but it will need huge computational resources. Typically the value of $\epsilon$ ranges from $10^{-3}$ for shapes as simple as sphere to $10^{-6}$ for complicated shapes.

When the iterative procedure is converged, a potential filed is said to be established and one of the three required parameters is obtained for every point of the domain.

iv. Streamlines: Streamlines are flow lines or gradient lines. They are orthogonal to potential shells. Thus, they can be characterized with $\nabla \phi$. A streamline is a curve which starts from the boundary, intersects the potential shells orthogonally and proceeds towards the shape center. In a convex shape like the case of a spherical shape, the equipotential surfaces are just different concentric spheres within the domain, the shape center being the same as the geometric center of the sphere, the radial lines will be the streamlines and they evidently intersect the concentric spheres orthogonally. In general domains, they may curve in order to satisfy the orthogonality criterion. The streamline tracking problem is essentially equivalent to solving an ordinary differential equation. If $X(t) = [x, y, z]^T$ is a coordinate vector, then the differential equation for streamlines is $\dot{X}(t) = \eta \nabla \phi [X(t)]$ where $\eta$ is called the normalization parameter. Runge-Kutta method with adaptive step size is used to solve this system.

v. Mapping the Domain: Volumetric Parameterization: After the streamlines are tracked, the end-points of the streamlines approach the shape center with unique sets of angles (polar ($\theta$) and azimuthal ($\psi$) angles). The end points of the streamlines are obtained in the Cartesian coordinate system. We apply the Cartesian to spherical transformation to obtain these angles ($\theta$ and $\psi$) desired for the mapping as, $\psi = \tan^{-1}(y,x)$, $\theta = \tan^{-1}\left(\sqrt{x^2 + y^2}, z\right)$. Since the genus-0 domains are topologically equivalent to a sphere, once these angles are available, we can use the set of parameters ($r, \theta, \psi$) to create a sphere of unit radius by computing $x' = r \sin \theta \cos \psi$; $y' = r \sin \theta \sin \psi$; $z' = r \cos \theta$; where $r = 1$ for unit sphere. In other words, given domain is mapped to a sphere. Once the mapping is established, the bijectivity can be demonstrated.

Results and Discussion
The entire algorithm was implemented using the C programming language. Two representative cases from the results obtained after testing the proposed algorithm on several complicated models is presented. It can be seen that there is no bijectivity loss in the mapping of a domain, which establishes the algorithm. The utility if the parameterization is also verified by using the results in path planning, shape matching (not reported here due to lack of space). A model of the star fish with 2745 vertices and 9761

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triangles is shown in figure 2 and corresponding atlas in figure 3. Another domain of molecule shape () is shown in figure 4 and its atlas in figure 5.

**Conclusions**

In this paper, a novel approach is presented to parameterize the volume of a 3D non-convex domain using harmonic function theory. Such volumetric parameterization can be utilized for path planning and shape matching applications.

**References**


Extended Abstract 65

Title
Template-based geometric transformations of a functionally enriched DMU into FE assembly models

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Keywords
Assembly, DMU, CAD – CAE integration, Functional information.

Introduction
To speed up a product development process (PDP), companies face increasing needs in setting up finite element (FE) simulations of large sub-structures of their products. The challenge is to study the behavior of assembly structures containing up to thousands of components [2]. Nowadays, time and human resources needed to pre-process CAD models derived from Digital Mock-Ups (DMUs) into FE models prevent from setting up structural analyses. Very tedious tasks are required to process the large amount of components and their associated connections. Aeronautical structures are particularly complex to transform due to their many independent connectors such as bolts or rivets.

Currently, research in CAD-CAE integration has focused on the use of global geometrical transformations of standalone CAD components [4]. However, this is not sufficient to pre-process FE assembly models because mechanical joints and interfaces tightening the different components must be part of this pre-process. Few contributions addressed the automation of assemblies pre-processing and they were restricted to contact areas to create non-manifold assembly meshing [3]. However contact areas are not sufficient to pre-process DMUs. To adapt an assembly to FEA requirements, geometric transformations derive from simulation objectives and components’ functions are needed to geometrically transform groups of components. It is also critical to structure the geometric models of components so that their shape transformations can preserve the DMU consistency [2]. We propose an approach where a DMU is enriched with interfaces between components (contacts and interferences) and functional properties. From this enriched model, simulation objectives can be used to specify geometric operators that can be robustly applied to automate components and interfaces shape transformations during an assembly preparation process.

Main Idea
DMU models are the reference geometric representation of a product used by structural and systems engineers. However, in the aeronautical industry, due to size and robustness constraints, this product representation is reduced to a set of components located in 3D space with respect to a unique global reference frame. No geometric relationships exist between them to avoid the complexity of geometric constraints propagation under DMU modifications. FE simulations need information about geometric interactions between components to propagate stresses and strains. In a first place, it is mandatory to enrich the DMU with geometric interfaces between components, i.e. contacts areas, interferences. With this first level of information, the components become geometrically connected.

![Initial Geometry](image1)

![Functional Interfaces](image2)

![Functional Designation](image3)

Fig. 1: Enriching the model of a screw with functional properties based on the analysis of its geometric interactions.

The analysis of FE assembly model preparation proposed in [2] led to the conclusion that FE models need functional information to set contact model parameters and to robustly identify repetitive groups of components such as bolted junctions. A DMU does not contain explicit functional information because component names are not robust, do not designate detailed functions, e.g. cap screw, set screw, clamping cap screw, etc. and are not connected to the geometric model of a component. In a second place,
we therefore assign functional designations to components and structure the geometric model of each component. In particular, we propose to enrich a DMU with structured components, i.e. some components are assigned functional designations, their geometric interfaces are inserted in their B-Rep description, other function-related components and interfaces contribute also to the structure of these components (see fig. 1). This is obtained with Shahwan’s approach, which exploit 3D geometric analysis to reveal functional properties of components and their interfaces [4].

As a result, the DMU is now geometrically structured, components are linked by their geometric interfaces, and group of components can be accurately identified and located in the DMU using their functional designation and geometric structure, e.g. bolted junctions. The geometric transformations needed to adapt the DMU to FEA objectives are thus strengthened because screws, nuts, counter nuts can be now robustly identified, groups of tightened components are also available through structured components.

Fig. 2: (a) CAD Model with functional designations and geometric interfaces, (b) model after template-based transformation of bolted junctions, (c) mesh assembly model with friction area definition.

To prove the validity of our approach and the methodology proposed in [1-2], we developed a prototype dedicated to automate transformations of bolted junctions. From an objective of FEA, e.g. detailed stress distribution around bolts and friction modeling within the Rotscher’s cone around them, a user-defined shape transformation template can be set up (see fig. 2). Any bolted junction can be used to define the template: merging screw, nut and counter-nut into a single domain, reducing the screw and nut shapes to a simple component of revolution while preserving the consistency of its interfaces. There, the structured components play a key role. This operator simplifies a bolted junction to precisely monitor the mesh generation. Around the bolt, a sub domain can be set up that model the extent of the Rotscher’s cone. Then, the functional designation of component and the component structure can be used to intelligently instantiate the template, i.e. instantiations take into account the number and thicknesses of tightened components, the screw diameter, length and head type (conical versus flat ones) in addition to the location of each bolted junction.

The final CAD assembly model associated with additional information on functional designation of components and attributes on geometric interfaces is ready to be exported to CAE software such as Abaqus. Meshing strategies can be efficiently applied with friction area definition.

Conclusions
In this work we present a template-based method enhancing the use of DMUs enriched, with functional information and geometric interfaces, to automate CAD assembly pre-processing in order to generate a FE-friendly equivalence. The resulting model produces a seamless generation of FE models conforming to the simulation objectives while taking into account meshing constraints. The current setting reveals highly tedious and manual tasks while the results obtained with an industrial example show the merit of the template-based approach and its valuable contribution to a PDP.

References
Extended Abstract 66

Title
Collaboration Platforms and the Effectiveness of a Virtual Team: A Case Study

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Keywords
Virtual Team, PACE project, Web-groupware, collaboration platforms

Introduction
There is plethora of collaboration platforms available for the collaboration between groups at different locations. These platforms, mainly web-groupware, have been developed to meet with the increasing presence of virtual teams. Virtual teams are globally dispersed working groups that interact mainly through collaboration platforms [1]. Collaborative engineering design relies upon the ability of distributed teams to communicate the main objectives of the project, to share a common vision of the design task and to understand the process and roles of each member on the team [2]. Collaborative engineering team performance is influenced by the methods and tools used to solve any issues caused by the geographical dispersion nature of the project.

This study is focused on the interaction and project results of a virtual team in the Partners for the Advancement of Collaborative Engineering Education (PACE) program. In the PACE program educators and students from Tecnológico de Monterrey in México, Virginia Tech & Howard University in the USA, Darmstadt University in Germany and Shanghai Jiao Tong University in China collaborate to redesign an electric car. The students were enrolled in either the senior year of an engineering graduate program or in a graduate science program and had previous experience related to the use of communication tools and CAD systems. The multidisciplinary and transnational nature of this project sets a framework where the use of collaborative and internet-based software is a requirement for the success of the project [3,4].

This work is preceded by similar PACE program ventures such as [1] and [7]. Unlike previous works on virtual team effectiveness, this study concentrates on collaboration platforms. This work also makes extensive use of the literature review presented by [8]. This paper presents a set of modifications for the existing methodology of design practices based on the selected group’s completion of the PACE project objectives. This paper intends to increase the validity of previous findings on virtual teams.

Main Idea
A project done by a virtual team in the PACE program will be used as a case study to analyze collaboration platforms and the effectiveness of virtual teams for product development. The PACE initiative was formed in 1999 by EDS, Siemens, Autodesk, Hewlett Packard, Sun Microsystems and General Motors. PACE partners provided the participating academic institutions with state-of-the-art hardware and software for CAD/CAM/CAE and PLM to create good technological conditions for teaching and research, at strategically selected academic institutions worldwide [4,7]. Currently the PACE program is focused on, requirements and planning (concept development), styling (Conceptualization), product engineering (detailed design), simulation (validation, optimization), manufacturing engineering (tooling, machining, 3D plant layout) and management development environment (product data management, supply chain management, digital collaboration). The project objectives are centered on the use of CAD and CAID software such as NX and Alias.

This work studies the document sharing, communication and project planning done by a virtual team through different collaboration platforms such as Basecamp, Skype, Gmail, Google Docs, Teamcenter Community and Snagit. The strengths and limitations of each platform are presented. The final written report and the final presentation are used to determine the success of the virtual team collaboration based on the completion of the projects objectives. The written report is a 58 page document and the final presentation is a Powerpoint document with 22 slides. The presentation was delivered in 15 minutes and was followed by a set of question and answers. Additionally, during the grading ceremony three remarks were made by the judging committee.

Interaction through Collaboration Platforms. The interactions through collaboration platforms are documented. This work discusses the limited capabilities of collaborative programs, lack of emotion in communication, limits on personalization of interfaces, unclear roles and responsibilities, time zone conflicts and over-communication. Figure 1 shows the discussion inside a to-do list in the Basecamp platform which links to documents in Teamcenter Community and Google Docs.
### Key Issues Identified in Project Deliverables.

The success of the analyzed project will be based on the effective use of the engineering design process. Main project objectives include a market research, concept generation, concept selection, engineering analysis and optimization, CAD models and a compelling presentation. CAD model sharing was imperative to develop different components of the project.

### Conclusions

This work provides a set of modifications for the existing methodology of design practices for product development. This study also increases the effectiveness of virtual teams by providing information on collaboration platforms and the appropriate use of these tools. This work presents a five week car redesign project developed by a virtual team of 14 people from four different countries. The way in which products and projects are developed has changed; the intensive use of information technologies is necessary, and not an option. Further work is needed to validate modifications on methodology of design practices.

### References


Extended Abstract 68

Title
Design of a Desktop Haptic System driven by CAD and Multi-body Systems Associativity

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Keywords
CAD parametric integration, CAD associativity, Multi-body interaction, Desktop and portable haptic device.

Introduction
This paper describes a methodology, which supports designers in the evaluation and modification of aesthetic virtual shapes. This methodology includes the advantages of using the associative data to both CAD and multi-body tools and thus maintaining the parametric dependencies between them. In this way, as the parametric data model gets modified according with the designer needs in the CAD system, the changes are consistently reflected in the multi-body environment. Modifications on the virtual shape can be done by using a global approach or by using a CAD drawing, then the data model in the multi-body environment is used to render a real 2D cross-section of the aesthetic virtual shape through a Desktop Haptic Interface (DHI), which allows a free-hand interaction with the aesthetic virtual object. The DHI is linked to the multi-body environment by means of using MATLAB and Simulink in order to control their servo-actuators. We also present the results of the validation process specifically carried out to evaluate the accuracy and the effectiveness of the DHI while renders 2D cross-sections of a virtual shape.

During the development of new concept products, designers need to physically interact with the evolving shapes of the product they are designing so as to check and evaluate aesthetic features of the products. The satisfaction of this need requires the production of physical prototypes. Before of building up a physical prototype a design engineer has to work with two or more software packages at a time for modeling and analysis in order to check all the constrains applied throughout the engineering processes. In fact, there are several commercial CAD, and multi-body software tools, which are widely used in the design industry. Most CAD software can provide a geometry model in standard formats such as STL, STEP or IGES, which can be used as the input in a multi-body analysis. Some of the major problems associated in the past with CAD and multi-body integration are information losses and breakdown of the parametric properties of the CAD model.

With regards the real 2D cross-section rendering process through the DHI, the device allows a continuous and smooth free hand contact interaction on a real and developable plastic tape actuated by a servo-controlled mechanism. The objective in designing this device is to reproduce a virtual surface with a consistent physical rendering well adapted to designers needs.

The DHI consists in a servo-actuated plastic strip that has been devised and implemented using seven interpolation points. In fact, by using the MEC (Minimal Energy Curve) Spline approach a 2D cross-section of a real surface is rendered taking into account the CAD geometry of the virtual shapes. In this way, the design process can also be controlled according to the well-defined engineering concepts and technical drawings. Considerable research has been done on CAD, and multi-body integration and associativity in previous years. In [1] the problems associated with CAD and CAE interoperability are described while in [2] suggest the incorporation of feature based modeling and analysis for CAD ad CAE integration, including all geometric and non-geometric ones. However, their work did not investigate the automation mechanisms to reapply engineering constraints in the design process as for example, geometric and distances constraints.

Main Idea
The methodology is arranged in such a manner that its flexibility follows the conventional, integrated and parametric design product process. Our methodology preserves the identities of the CAD components and the corresponding imported components of the multi-body simulation environment. In fact, this associativity is a mapping between the parts and their constraints in the CAD assembly and the corresponding body and joint blocks, coordinate systems, and subassemblies in the multi-body generated from the CAD assembly. In other words, it captures the identities of the CAD components through their topology. However, this associativity is not completely symmetric between the CAD and the multi-body environments, because the translation process moves in only one direction, from the CAD to the generated multi-body model.
Figure 1-a shows the associative approach used in the methodology between the 3D model, the CAD integration and the DHI. Figure 1-b shows the multi-body and the DHI interfaces driven by a parametric CAD drawing (e.i. any dimension can be modified, then the multi-body environment is updated and the DHI renders the new 2D cross-section).

Fig. 1: CAD Integration between the software tools: (a) Associativity approach, (b) Multi-body and Desktop Haptic Interfaces driven by a CAD drawing.

Fig. 2: User interaction with the system. (a) The haptic interface while moving along “X” axis, (b) User’s hand while touching the strip, (c) The 3D object while rotates around “Z” XIS and (d) The haptic interface while rendering the 2D cross-section.

At this step of the methodology, the user is able to feel with the palm of the hand the real 2D cross-section in order to evaluate the quality of the shape (such as in Figure 2).

Before reaching a final satisfactory product representation, several loops are carried out and, therefore, several physical prototypes are developed during the design process. Moreover, each time a physical prototype is required for evaluating the product, the design process halts, waiting for its construction.

Conclusions
In this paper we have presented a successful methodology to physical render a 2D cross section of a virtual object. The methodology and the Desktop Haptic Interface that we propose here reduce the number of physical prototypes during the design process and shrink the design time by allowing the evaluation and modification of the product shape and surface earlier. On the other hand, our system allows designers to perform all the phases of the product design process (concept, modeling, visual and physical evaluation and modification) continuously and without any interruption.

References
Extended Abstract 69

Title
Scalable Integration of Commercial File Types in Multi-User CAD

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Keywords
Collaborative design, concurrent engineering, multi-user CAD, CAE

Introduction
Current commercial computer aided design (CAD) tools limit concurrent engineering, or the ability of product development teams to work in parallel, by only allowing a single user in the CAD environment at a time [2]. The NSF Center for e-Design, Brigham Young University (BYU) has developed multi-user CAD tools which enhance concurrent engineering capability by allowing multiple users to concurrently contribute to the same part or assembly in real time. This includes the ability to concurrently view and modify the same part or assembly in a shared CAD environment. However, the combined challenges of consistent distributed naming and robust interoperation with commercial file types have created scalability and usability issues for previous multi-user CAD implementations. This paper presents persistent naming methods and a file-based architecture that overcome these challenges.

Scalable interoperation with commercial CAD file types
Extending a single-user CAD system to be multi-user requires the definition of a format for data exchange, so that the most up-to-date state of the model can be stored on the server and so that operations performed on one user can be transmitted to other users. The server uses a database to store this data. Each type of operation requires its own explicitly defined database representation, so feature types must be made multi-user one by one. In practice, given the huge and growing variety of data types within any given CAD system, explicitly creating database representations for all of them is very time consuming, so attempting translation has almost always resulted in some degree of data loss. Because of these and other challenges, no systems prior to BYU’s multi-user CAD implementation have allowed a real-time, multi-user experience with commercial file types. BYU’s early approaches have shown to directly operate with commercial file types with small parts and assemblies; however, it has challenges scaling to large parts and assemblies due to issues with unreasonable load times. This paper presents a scalable methodology and implementation that overcomes this and other related challenges associated with previous multi-user implementations for commercial CAD.

In order to use commercial CAD files with a cloud based multi-user CAD system, a new method has been developed to store database associativity within a CAD file. Where previous methods create a system to map memory handles to unique identifiers and storing that map in the client plugin, this method uses unique identifiers stored in a user-defined attribute directly associated with each object in the CAD part. Storing the unique identifier in the CAD system’s native part file makes it possible to restore the state of the multi-user CAD tool, including association data, just by opening a commercial part file. This removes the need to recreate the part or assembly object-by-object. The new process increases scalability in multi-user CAD tools by drastically reducing load times in part and assemblies containing several objects.

The implementation of the hybrid file multi-user feature identification method in a multi-user CAD application imbedded in Siemens NX, called NXConnect, has shown to vastly decrease load times. For one part file that had approximately 100 features, the load time was reduced from 2 minutes to 3 seconds. In another test, a tractor model assembly with 16 components loaded in 7 seconds, which is approximately 1% of the 10 minute load time of the former method. Where the previous loading implementation prevented the scalability of NXConnect due to unacceptable load times, the new loading method introduces almost no additional wait time beyond the time needed to download the part. Thus it is shown that this new methodology provides a scalable approach for commercial multi-user CAD to be compatible with large, complex assemblies and parts.
Persistent Multi-user Topology Identification

Another issue related to implementing a multi-user environment within an existing commercial single-user CAD tool, as mentioned by Red et al., is that CAD APIs generally do not easily facilitate passing design changes between multiple users. This is illustrated by the fact that when a CAD object is queried on a client’s CAD system, it returns a memory address specific to that client, which is not consistent between clients [1]. When an object on one client is changed, the client must be able communicate to the server which object changed so that all other clients can identify, in their own CAD system, which object the change refers to. Each object must therefore be uniquely and consistently identified across all clients and the database. As memory address pointers for given objects differ across clients, they cannot be used as consistent identifiers. Alternative methods must be identified for finding the unique identifier corresponding to an object in a part and for finding the object corresponding to a unique identifier. This paper discusses a robust method and implementation for supporting topology identification.

The identification of bodies, faces and edges must be consistent across multiple clients because they are referenced in the creation of features, curves, expressions, dimensions and constraints. However, doing this offers some unique challenges. For example, bodies, edges and faces in the Parasolid geometry kernel are “not returned in any predictable order” [3]. Therefore it requires custom methods to identify the same bodies, faces and edges in a part across clients based on their geometric, topological and feature qualities. Methods have been developed to identify common bodies, faces and edges across clients and are executed in the following order:

1. Edges are identified by querying data on the edge at discrete values along its length with a given tolerance
   a. Linear edges will only require end point data
   b. Non-linear edges may require more resolution to uniquely identify
2. Faces are identified by querying data at discrete values across the face with given a tolerance
   a. Planar faces will not require discretization if all edges are identified uniquely. This is because they can be inferred from the bounds of the edges
   b. Non-planar faces may require more resolution to uniquely identify
3. Bodies are identified by using all of its faces and edges which are already identified

The persistent topology naming method has allowed complex geometry associations to be produced in NXConnect. Despite the fact that the NX API has known bugs which cause errors to occur in the NXConnect implementation for this method, the approach is shown to be reasonably robust. This is shown by the use of an internal tracking system to observe the robustness of this implementation. Over a three-week period, about 22 active users clicked at least 1771 body-generating commands. Each command could generate multiple bodies, or if the user cancelled the command, no bodies. This period included significant large-scale modeling. During this period of use, only 22 invalid bodies were created. Assuming an average of one body per body-generating modeling command, this suggests the topology naming scheme is approximately 99% effective.

Conclusion

The newly developed method to associate CAD objects directly to the database using CAD object attributes has shown to increase part and assembly scalability in multi-user CAD tools by dramatically reducing part and assembly sync time. This time reduction grows significantly as object count increases in a part and assemblies. Another major benefit is that the methodology seamlessly integrates commercial CAD parts into a multi-user CAD implementation. The persistent topology naming methodology solves the problem of multiple users referencing the same topology entity on separate clients. Due to limitations in the NX API, the implementation has required additional redundancy to be implemented effectively, but has shown to be robust enough to support modeling of complex parts and assemblies. The results of these implementations have been very promising for the future development of multi-user solutions for commercial CAD.

References

Extended Abstract 71

Title
Algorithm for directional projection of parametric curves onto B-spline surfaces

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Keywords
Directional projection, B-spline, Curves on surfaces, Approximation

Abstract
Directional projection of curves onto surfaces are widely implemented in CAD (computer aided design) systems [1, 2]. It plays fundamental roles in many operations, for example surface cutting, model designing, etc. It can also be utilized as a tool for constructing curves on surfaces. Given parametric curve \( P(t) \), a projection direction \( \text{Dir} \) and surface \( S(u,v) \) in 3D space, the directional projection of \( P(t) \) onto \( S \) is defined like this. Letting \( p \) denote an arbitrary point on \( P(t) \), the directional projection of \( p \) onto \( S \) is a set of points \( q \) on \( S \), which satisfies the following rules:

\[
(q - p) \times \text{Dir} = 0
\]

and \( (q - p) \cdot \text{Dir} > 0 \) holds. As we move the test point \( p \) along \( P(t) \), the motion of \( q \) results in a set of points on \( S \), and that is the directional projection curve (see Fig. 1).

![Fig. 1: The definition of the directional projection.](image)

To compute the projection curve, first order algorithm were proposed in [3]. They derived the first order differential equation systems. By solving the system with numerical methods, they got a sequence of points along the projection curve. Then the approximate projection curve could be obtained using the interpolation method on the point sequence. There are some drawbacks in the first order algorithm above. First, the step length of the points they got along the projection curve is not well controlled, which results in the unevenly distributed points and directly impact on the approximation result. Second, the approximate curve does not lie on \( S \), which is unacceptable in many CAD applications [4]. The approximation precision of the approximate curve cannot be controlled, and they cannot deal with the “jumping” projection case.

![Fig. 2: The processing result of jumping.](image)

In order to overcome the drawbacks of the first order algorithm, we provide an algorithm dealing with the directional projection of parametric curves onto B-spline surfaces, which approximates the exact directional projection curve with a piecewise curve on \( S \).

We derived the first and second order differential equation system, and approximate the pre-image curve of the exact projection curve with its second order Taylor extension, which is a better approximation than the first order equation system.
used in [3]. With the second order differential equation system we can compute the Hausdorff distances between the approximate curve and the exact projection curve using iteration methods, which enables us to control the approximation precision and the continuity of the approximate curve [5]. We also deal with the “jumping” case projection as plotted in Fig. 2, which frequently appears in practical.

We compared with the first order algorithm [3] both on efficiency and precision. Experimental results indicate that the accuracy of our algorithm is comparable with that of the first order algorithms [3], and at the same time our algorithm is faster than them. Moreover, our algorithm can deal with the “jumping” case, and control the approximation precision and the continuity of the approximate curve, while the first order algorithm [3] cannot do this.

Fig. 3: Common case projection: (a) surface of the stomach of Venus, (b) surface of woman face, (c) projecting characters onto free form surface.

Fig. 4: "Jumping" case projection: (a) tour surface (in NURBS form), (b) projection curve crosses the boundary of the surface.

Fig. 3 demonstrates the performance of our algorithm in the common case projection. And Fig. 4 demonstrates the performance of our algorithm in the "jumping" case projection.

Generally speaking, the efficiency of the algorithm meets the real-time requirement. And our algorithm can perform “jumping” checking and controls the approximation precision and the continuity of the final approximate projection curve, the existing first order algorithm [3] cannot deal with.

References
Extended Abstract 72

Title
Minimization of Bone Removal Through Optimal Humeral Implant Alignment in Total Elbow Arthroplasty

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Keywords
total elbow arthroplasty, bone removal, implant insertion, flexion-extension (FE) axis alignment/malalignment, outer and inner bone contours, implant posture, total interference minimization, global optimization search

Introduction
Total elbow arthroplasty (TEA) surgeries are generally characterized by low incidence and low 10% revision rates [2]. As a result, orthopaedic surgeons tend to have insufficient exposure to the procedure which translates into their inadequate familiarity as well as proficiency with its steps. According to current standards for TEA procedures, surgeons are to rely on jigs and/or gauges in order to determine intraoperatively the position and orientation of the native flexion extension (FE) axis of the elbow joint. After the medullary canal of the humerus is exposed through partial or total osteotomy of the distal portion of the bone, various broaches and/or reamers are used to enlarge it in order to facilitate the subsequent insertion of the humeral implant which would be otherwise impossible [3]. Owed to the lack of effective cues, bone removal operation relies almost exclusively on surgeon’s expertise, and hence an increased possibility exists to significantly diminish the strength of the bone [1] through excessive cutting. As such, the total amount of cortical bone to be removed during TER should be minimized at all costs in order to avoid the extensive use of bone cement, often leading to non-ideal loading conditions of the implant. Moreover, appropriate measures have to be taken to limit the amount of malalignment between the native and prosthetic FE axes of the elbow in order to warrant the long term success of the surgical procedure and thereby improve the overall patient outcomes and quality of life. The complexity of the problem is considerably elevated by the anatomical diversity of the humeral geometry which essentially makes each implantation procedure unique.

Main Idea
To address this, the current study proposes a generic methodology capable to minimize the amount of cortical bone to be removed from the walls of the endosteal canal in order to allow implant insertion by simultaneously preserving as much as possible the alignment between the FE axes of bone and implant. For this purpose, a two-step numerical procedure was developed involving: i) generation of unequivocal discrete point-based representations of cortical bone contours from automatically segmented polygonal meshes yielded from CT scans of the humerus; and ii) constrained numerical optimization aiming to minimize the amount of cortical bone removed through the adjustment of the implant posture.

The algorithm used to determine the point dataset approximating inner and outer bone contours was primarily based on the nearest neighbor approach used in conjunction with few other point-based data cleaning techniques required to eliminate the self intersections/voids/islands and other types of data anomalies (Fig. 1a) that were inherited from the original input file provided in a specific polygonal mesh format (*.vtk) yielded as a result of the automated segmentation of the CT data typically performed by means of marching cube algorithm. The main output of the first data processing step consists of a cloud of points which clearly delimits the two contours of interest of the osseous specimen (Fig. 1b-e). This clear distinction between outer and inner contours of the cortical bone is of utmost importance for the subsequent phases of the developed methodology. For any given posture (e.g. position and orientation) of the implant relative to humerus, the status of each of the stem points has to be unambiguously identified between interference or non-interference condition, i.e. “inner” or “outer” bone boundaries.

The constrained numerical optimization performed in the second step relies on a bounded nonlinear search to identify suitable candidates for implant postures. In terms of input variables, 6 variables/DOFs (three translations and three angles) were used to uniquely characterize the posture of implant FE axis with respect to the native FE axis of the elbow. In common clinical terms, these variables were identified by the distance between the geometric centers of the capitellum (native and prosthetic), and flexion-extension (FE), internal-external (IE) and varus-valgus (VV) angles (Fig. 2a-d). The inherent assumption made – in agreement with standard TEA practices – was that the native FE axis of the elbow is determined by the line connecting the two geometric centers of capitellum and trochlea sulcus of the humerus as...
Fig. 1. Extraction of discrete cortical bone contours from automatically segmented polygonal meshes: a) sample of slice-based raw bone contours; b) cleaned bone contours; c) discrete representation of intact distal humerus; d) outer points on excised distal humerus; e) endosteal canal points on excised distal humerus

approximated with a sphere and circle, respectively. To facilitate numerical iterations, an appropriate quantitative metric has been defined for bone/implant interference amount, essentially by summing up the maximum interference amounts determined in each slice (Fig. 2e). The employment of the developed numerical technique has a double advantage: a) enables the minimization of the amount of bone to be removed through a more judicious positioning of the implant; and b) enables a facile (graphical) identification of the zones from where the bone should be removed in order to allow the adequate positioning of the implant within the medullary canal.

Fig. 2: Definition of the optimization parameters and objective function: a) capitellar translation, b) flexion extension angle, c) varus-valgus angle, d) internal-external angle, and e) maximum interference amount per slice.

Conclusion
Current protocols for TEA might result in excessive bone removal and/or large implant malalignments, both with negative consequences on the clinical outcomes of the surgical procedure. The proposed method can serve as a valuable reference tool in determination of the location and amount of cortical bone to be removed in order to minimize implant malalignment. The implementation of the developed computer-assisted techniques in routine preoperative practice will likely reduce the incidence and severity of complications currently experienced by TEA patients.

References
Extended Abstract 73

Title
Notes on Generative modeling, Procedural Symmetry, and Constructability of Architectural Design

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Keywords
Generative modeling, Procedural symmetry, Constructability

Introduction
Prior to the development of industry, manufacturing was often done at homes or workshops, using hand tools or basic machines. Designers were also fabricators of their own works. When it was necessary, design was expressed as fabrication processes, such as recipes for cooking. As design and fabrication were separated into different jobs, designers created specifications to the artifact, and fabricators manufactured in respect to the specification. The work of a designer was shifted from the creation of artifacts to making drawings that specify the artifact. The situation steeled the shift of paradigm over design thinking and education, most conspicuously, in architecture. Architects are trained to be experts of drawing drawings, instead of building buildings.

Drawings are abstract representations of artifacts. Architectural design drawings such as plan, elevation and section are abstractions based on the geometric symmetry of buildings along orthogonal directions. Computer aided design systems create and manipulate geometric objects based on symmetric features of forms. For example, commands for creating geometric objects make uses of the symmetry underlies primitive shapes like circle, cube and cylinder. Commands for manipulating shapes such as move, rotate, copy, array, offset, as well as commands such as extrude, revolve and the likes are also applications based on the geometrical symmetry. Designing consists of the act of realizing the symmetric features of the form in mind, and the act of realizing what are imagined into drawings with commands in the CAD system in use. Symmetry is the key for the reduction of information. In a drawing or model, additional information is desirable wherever symmetry is broken. A rectangle with asymmetrical sides requires additional information to specify its length in addition to its width. Conventional buildings are more likely to have orthogonal and linear forms, within which symmetry prevails as transformations of shapes remain consistent along orthogonal axis.

The symmetrical features of building design are strongly related to constructability. For building design with symmetrical shapes, dimensions and interfaces, systematic and prefabricated construction methods are more applicable; material and parts can be massively fabricated; engineers and workers take less effort in communication and control; tools, machinery and equipment can be reused. Constructability concerns the reduction of information. Fisher [1] summarized design variables that contribute to the constructability of reinforced concrete structure as follows:

1. Dimensions of elements (e.g., height, depth, width, thickness and length)
2. Distances between elements (e.g., clear spans and story heights)
3. Changes in dimensions and distances (e.g., from floor to floor or from bay to bay)
4. Quantity and type of reinforcement
5. Concrete strength
6. Repetition of dimensions and distances, and modularity of layout

The third, fourth and the last variables are related to geometrical symmetry of layout, element and reinforcement. Number one and two are related to the compatibility between the design and construction systems such as tunnel form and flying form, many of which were devised based on the symmetry of forms. Constructability also has much to do with the symmetry in processes. Figure one shows two different ways to build igloo. On the left, the igloo is built by laying snow bricks onto a sloped spiral curve to the top. The igloo on the right shows that snow bricks were arranged horizontally as circular rings on top of the other with reduced sizes. According to a documented film in 1949 by D. Wilkinson (National Film board of Canada) [2], the Inuit build igloo with the spiral design. The circular design of an igloo might be more natural from a designer’s standpoint, for its geometric symmetry is more apparent and is easier to draw and model with pencils and CAD systems. However, the spiral design of igloo has the advantage over constructability. The spiral design sacrifices the geometrical symmetry of snow bricks for
procedural symmetry. For every brick that is being laid is supported by bricks underneath and the brick on the down side of the slop. With the circular design, procedural symmetry is broken when the first snow brick of each layer has to stand on the tilted top of the lower layer without getting any support from both sides. Procedural symmetry is broken again when the last snow brick of each layer has to fit into the space within blocks on both sides. In the construction process, additional information is necessary for handling asymmetrical situation and action.

![Fig. 1: (a) The spiral design of igloo  (b) The circular design of igloo](image)

In conventional CAD systems, results of geometric operations are the focused objects for further operations. Procedural information regarding how designers build up their design models is merely kept at the most primitive level, for implementing the undo/redo function basically. Tools are hardly provided for the manipulation of process. Procedural symmetry are not recognized and recorded in the design development. Generative modeling is an aged-old paradigm, within which processes are the focused subjects of modeling, while shapes are by-products. It concerns “how” to generate the shape, rather than “what” the shape is composed of. Most commercial CAD systems have adopted the “what” strategy instead of the “how” strategy for the modeling of buildings. Generative Modeling Language [3] was proposed as a programming language, in which PostScript was used in GDL as the fundamental scripting structure for modeling the process of modeling. Generative Component and Grasshopper are add-ons of commercial CAD systems that were developed based on the generative modeling paradigm.

In this paper, it is suggested that generative modeling enables designers to record and reuse the information of shape generation that would otherwise be lost if the CAD tool can only manage what the designed shape is composed of. The lost information could have been useful to capturing procedural symmetry, and reducing cost of design operation and communication, which would enable knowledge integration in early design stages. Architectural design cases that use generative modeling to integrate necessary domain knowledge to increase constructability with regards to structure, environmental impact, and construction issues are displayed and analyzed.

References
Extended Abstract 75

Title:
A development of tailor-made design system for arm brace

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Keywords
Brace, Tailor-Made Design, Reverse Engineering, Mesh Deformation, Tensegric Modeling, t-FFD

Introduction
A brace is an indispensable device for disability persons with disorders at their limbs, and assists their rehabilitation and daily life. In order to obtain the optimal effect, its shape is required to fit to an individual limb, and the tailor-made is the most effective manufacturing method. In the traditional way, since all the processes are performed by handicraft of well-trained prosthetist with official qualification, the cost is not negligible. Also the mold cannot be reused, and the quality of a product is non-uniform.

Recently, the digital manufacturing systems of tailor-made prosthetic limb and brace have been developed, and we can see the dedicated CAD systems. Clin’s method [1] was developed for torso brace design. In the method, torso model is represented by personalized finite elements, and the system simulates the shape deformation based on the geometrical constraints given by the brace model. Facoetti’s method [2] was developed for socket design of lower limb prosthesis. In the method, an operator can design an optimal socket model according to the guidance based on orthopedic knowledge, and the model is represented free-form surface. However, since the product model is designed from scratch in these methods, it takes the time according to the complexity. So, these methods assume that the model has simple shape which is homeomorphic to disk or cylinder.

Also, personalized arm brace (Fig. 1) is in strong demand. However, since arm has high posture degrees of freedom compared with the other body parts, the brace has multiple feature shapes required for the function. So the conventional methods cannot be applied for the tailor-made design. In our research, we developed a tailor-made design system for arm brace. In this paper, we describe the details, and demonstrate the experimental results.

Main Idea
Our idea is that the tailor-made arm brace can be designed instantly by deforming standard brace as fit to an individual arm. In our method, a user inputs shape models and geometrical constraints to fit the brace model to the arm, and the system outputs the final shape automatically. The models are the brace model with standard shape (“standard brace model”, Fig. 2(a)), and its rough-shape model related to it geometrically (“control mesh”, Fig. 2(b)), and “arm model” (Fig. 2(c)). The standard brace model is deformed smoothly according to the constraints and the relation.

We assume that these models are already prepared in some way, and we designed by using reverse engineering technique in this study. Generally, the arm brace has some feature shapes locally, and the global shape which satisfies both of the constraints and fits to an individual arm is non-trivial. In the prototype system, a user inputs the models and the geometrical constraints, and the system outputs automatically the final shape which satisfies the requirements.

![Fig. 1: Arm brace (elbow brace)](image)

![Fig. 2: Input models of our prototype system: (a) Standard brace model, (b) Control mesh, and (c) Arm model.](image)
The deformation algorithm is based on “tensegric modeling” [3] and “t-FFD” [4]. Tensegric modeling is a pseudo physical simulation method for arbitrary meshes, and is applied to the deformation of the control mesh. t-FFD is a free-form deformation method for arbitrary meshes, and is used to calculate a final shape of the brace model from the deformed control mesh given by the simulation. In this method, the deformation process is performed automatically in accordance with following steps.

1. Establishment of correspondence relation between the brace model and the control mesh by t-FFD
2. Construction of deformation structure for the control mesh
3. Tensegric modeling based on the geometrical constraints
4. Restoration of the brace model based on the simulated result and the relation

A brace model can be deformed smoothly and globally by conventional t-FFD, but the boundary conditions based on the constraints are not considered in the algorithm. In this study, the geometrical constraints are achieved by implementation of a new mapping algorithm to the method. As a result, the final brace model has a smoothly deformed surface which fits to the arm model, and satisfies the constraints.

In order to verify the usefulness of our system, we performed the experimentations, and compared the final shape of the brace model with the initial shape (standard shape) of that (Fig. 3).

![Fig. 3: An experimental result: (a) Initial shape and (b) Final shape of a brace model. Each left side shows a relative position between an arm model and the brace model. Right side shows a color-map based on the maximum shape deviation of the brace model to the arm model.](image)

Conclusions
In our research, we developed a tailor-made brace design system. The experimental results based on our system indicated that the final shape of the arm brace can be designed to fits to an arm more than the standard shape. So we have confirmed that our system is useful for design of tailor-made arm brace. Since the personalized brace is designed by simple visual operations to the standard model, a user can get easily an optimal tailor-made arm brace. The system can achieve low cost manufacturing and high & uniform quality of the product compared with the old fashion. In our future works, we will try improvement of the fitness of the final brace model and implementation of a skeletal deformation module of arm to our system. Since the latter extension achieves a design of brace model fits to an arm model with desired posture from that with arbitrary posture, we think it can reduce patient’s load in the arm measurement.

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References
Extended Abstract 76

Title
A web-based platform to support contract furniture design

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Keywords
Web enabled design, collaborative product development, virtual engineering

Introduction
The contract market is a transversal business in the world of furniture, involving different types of products, from upholstered furniture to bedrooms, from office to bathrooms till outdoor furniture. It represents an increasingly important segment for furniture industry. Involved stakeholders are arranged into complex inter and intra temporary firm networks in which different interests, competences, abilities are brought to bear on products [3]. Increasingly innovative ways of exploiting the Internet is giving rise to potentially new ways of designing and managing contract furniture projects where team working is a key element of competitiveness. Many CAD applications have been developed to enable the incorporation of online information to facilitate collaborative product development in the extended enterprise but none of them is dedicated to contract furniture whose needs require a significant challenge in today Computer-Supported Collaborative Work solutions (CSCW).

This research aims to improve contract furniture design by developing a web-enabled solution capable to satisfy the need of the above-described network. This objective is part of a long-term research project, funded by the Italian Minster of Economic Development within Industria 2015 programs. Its final goal is the creation of a platform integrating e-marketing intelligence functionalities with online furnishing configuration and co-design tools based on virtual prototyping techniques and their experimentation on new hospitality concepts for luxury markets. The first stage of the project is the development of a platform supporting the following functionalities: online product configuration and 3D visualization of custom solutions, selection of personalized items and their integration into the 3D architectural environment, BOM creation and identification of products to be co-designed and finally management of the whole contract project.

The present work describes the adopted approach for the definition of the system architecture and the preliminary implementation results (i.e. integrated COTS components, programming platform and language, integrated commercial tools, dedicated plug-ins).

The web-based platform for contract design: approach and results
Contract furniture design involves interaction between actors situated at a number of sites along a commodity chain or network, including manufacturers, their suppliers, retailers, designers, consumers and marketers. The result of the network labor is the creation of a finished commodity for hospitality, offices, retail, restaurants, marine, etc. In this context, design cannot be seen as an isolated sphere of creativity, but it emerges from a wider field of relationships and knowledge of the entire network. Literature overview points out the multi-dimensional, multidisciplinary and multi-scale nature of contract furniture processes, services and products [5] and identifies the inner characteristics of furniture-dedicated products that are high-level customization according to the architectural space, the designer taste and style and the socio-cultural context, strong brand image, low manufacturing cost, eco-sustainability, high product durability and reliability, respect of international standards and reduced lead times [1].

New information communication technologies and web-enabled platforms have the potential to dramatically change furniture design, manufacturing and marketing [4]. These technologies are encouraging globalization, internationalization, cooperation, knowledge formalization and exchange. According to the process stage they can be classified into e-commerce solutions and CSCW applications. There have been many research efforts on enabling technologies or infrastructure to assist product designers in the CSCW environment [2], but none address contract furniture challenges. Some of them aim to help designers to collaborate with manufacturers by sharing product information and others to manage conflicts and support negotiation. Most promising ones provide a shared and distributed workspace where designers and manufacturers can access a product model, often in STEP standard, representing design information at several levels of granularity and check the status of their assigned tasks [6]. The review of CSCW applications highlights a lack of solutions dedicated to contract furniture able to
simultaneously support information exchange, temporary network reconfiguration according to the development stage and involved stakeholders, product and environment customization, management of multiple and conflicting design constraints and process requirements, creation of the furnishing BOM and distribution of product specifications to suppliers.

The effectiveness of teamwork and the critical need for communication in the context of contract furniture push the present research toward the development of a CAD-based and web-enabled platform capable of supporting the different phases of furniture design. A structured methodology is defined to achieve this purpose. It drives the definition of the system architecture on the basis of the specific needs of the use context. Its main steps are as follows:

1. Analysis of the AS-IS contract furniture process. Investigations are based on questionnaires and interviews submitted to 18 small and medium-sized Italian companies operating in this market niche. The analysis brings to the definition of the main development activities, collaboration issues, input/output data typology, furnishing features, product variants, involved stakeholders, etc.

2. Elaboration of the TO-BE interaction model and use case scenarios to identify the platform requirements;

3. Benchmarking of state-of-art IT solutions based on user requirements and TO-BE process needs. The assessed solutions are: furnishing configuration-oriented tools (e.g. Mobilia and Metron), 3D CAD modeling tools with web-enabled functionalities (e.g. Sketch-up), CAD-based design automation plug-in developed for general purpose CAD software, web-based 3D furnishing configurators (e.g. Sweehome3D, Domus planner), co-design systems supporting 3D model visualization (e.g. Autovue, SpinFire, Streamline). A 5-point scale is used to evaluate how systems are able to satisfy user requirements and a correlation matrix enables the identification of tools to be integrated into a comprehensive platform.

4. Definition of the platform architecture. A multi-user interface and the platform modules are stated, and the input/output data flows are outlined to drive the system development.

The application of the above-mentioned approach steps leads to the identification of two main system modules: a configuration module and a co-design one. The first allows the user to configure the 3D space by selecting and customizing the most appropriate items. It has three main interfaces: 1) a Virtual Catalogue (VC), which is a web-based marketplace where 3D solutions are presented and the user can assess all feasible variants for each product; 2) An Interior Design Configurator (IDC), that is the furnishing configurator allowing the user to create a contract project, import a 2D or 3D model of the architectural space, populate it with the customized items chosen within the VC, and arranging the setting environment according to technological, functional and aesthetics constraints and knowledge-based rules; 3) A Data Manager, which is a technical product configuration allowing product manufacturers to upload and define product variants and design rules. The Co-Design module enables the technical configuration of products or integrated design solutions by co-creating a web-based co-design space. It is necessary when the product variants offered are not able to satisfy a certain chance and a customized product is required. It consists of a technical collaboration area offering a shared space on the web to support product configuration in a collaborative modality and a workflow area for process monitoring. In the collaboration area all involved contract stakeholders actors can share the 3D product model, and discuss on it by audio-video conferencing to identify the necessary changes and to find out the best solution.

Conclusion
The research addresses the main challenges in contract furniture design. It provides a structured approach to create a supporting web-based platform to manage 3D furnishing configuration and collaborative product development in the extended and temporary commodity network. The work illustrates the result of the benchmarking of contract furniture-oriented technologies and the preliminary developments for platform implementation.

References

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10

Page 169 of 226
Extended Abstract 77

Title
Substituting Simple Structural Beam-Frame Substructures with Equivalent Beam-Plate Combinations

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Keywords
Stiffness matrix method; Automotive structure; Finite element analysis -based design; Beam-frame model, Sub-structure analysis; Simple structural beam-frame; Simple structural surface.

Introduction
The design of an automotive structure is critical to the overall performance of a vehicle. The structure of the vehicle is important to ensure that it can satisfactorily carry the applied loads that occur [1]. The vehicle structure interacts with all other vehicle sub-components and has a complex influence on their functionality. Due to the structural design complexity, the design process is traditionally conducted by trial and error and is subjected to numerous changes even in the latest stages of the design process. However, some of the changes in the design of structure may cause significant re-design of the other vehicle components and this process may become very costly. Typically, it is much more desirable to maximize the design changes during the early design stages and particularly, before the detailed design activities [2]. However, employing a very comprehensive and detailed process of analyses at the conceptual design stage, when a greater range of design choices is still available, may become very time consuming and computationally expensive. Therefore, it is very valuable for designers to employ simple but effective analyses at the early design stages. One option for conducting this analysis is through the use of a simplified vehicle structural model. The simplified model can be utilized to represent the geometric properties of the structure and then be analyzed and optimized in a numerical finite element program.

Being able to efficiently analyze the body structure during the conceptual design stages is important to determine the performance characteristics. A primary method employed to analyze the structure is the method of Simple Structural Surfaces (SSS) [1]. This method utilizes planar sheets to model the body structure. The SSS method can be used to determine the load-paths present in a body structure, but is unable to analyze an indeterminate static loading condition. Alternatively, the method introduced in authors’ previous work considers beam-frame elements to represent the structure as an equivalent space frame. The approach of using beam elements has the advantage of being able to determine displacements due to these forces by using the Finite Element Method (FEM). The beam-frame finite element model can be utilized for basic analysis of a vehicle structure and as an initial estimate of some important vehicle parameters such as the bending and torsion stiffness as well as some vibration characteristics. Using analogy of names, this method is referred as the Simple Structural Beam (SSB) method. This paper presents an approach to develop an optimized preliminary vehicle structural model. The SSB model of a structure is a space frame representation and is therefore, missing some planar sheet elements that are necessary in a typical vehicle structure such as the floor and roof.

Methodology
The development of the beam frame structure begins with transferring the geometry of an existing vehicle structure to an equivalent beam model. The first step of analysis is performed to determine the initial structure weight and stiffness values. This analysis and corresponding uniform beam section dimensions are used as initial values for a goal attainment multi-objective optimization. The optimization algorithm is employed to minimize the structure weight to stiffness ratios for both the bending and torsion stiffness. The beam section dimensions are considered as the design parameters that are varied during the course of the optimization. The beam frame structure that was developed is shown in Figure 1.
The optimization of the beam structure has been previously conducted and as such the focus of this work is the final stage of the preliminary model development [3]. As can be seen in Fig. 1 the beam model is missing the key plate components, such as the floor and roof. The work performed here seeks to determine a suitable thickness of each plate component (Fig. 2). A total of ten plates are considered in the above structure. The plates are analysed using a substructure analysis method. The substructure consists of a plate component bordered by a set of beams that are subjected to an optimization process using the same algorithm as the beam structure with a cantilevered loading condition. The applied loads are based on the internal beam loads that are developed in the optimized beam structure.

![Fig. 1: Beam Element Model](image)

![Fig. 2: Beam and plate combination for a quadrilateral substructure](image)

**Conclusion**

The development of an optimized preliminary vehicle structural model can reduce the time and cost involved in a vehicle development process. The utilization of a numerical program simplifies the analysis procedure and can allow for rapid changes in structural parameters. Optimization of the preliminary structure based on static loads ensures that the vehicle structure being analyzed is the best possible structure available.

**References**


Extended Abstract 78

Title
A feature and script based integration of CAD and FEA to support design of variant rich products

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Keywords
Finite Element Analysis, Computer Aided Design, ANSA, SolidWorks, LS-Dyna

Introduction
The focus of the research presented in this paper has been an integration of a CAD-system and a FEA pre-processor to automatically develop a complete FEA-model in order to make simulation based design possible.

One problem when integrating CAD and FEA is the meshing step. Commercially available CAD/FEA connections produce unstructured meshes consisting of tetrahedral elements. For some types of simulations, that kind of mesh is not sufficient but structured meshes are demanded. This is why many FEA-experts spend days to import neutral CAD-files into FEA pre-processors, healing the imported geometry, isolating interesting geometry and developing the structured mesh models.

In the literature, related work can be found. For instance, Sellgren developed a framework for simulation-driven design [1], in which simulation models were extracted based on the CAD-model relationships. Chapman and Pinfold described how to use KBE and FEA for the design automation of a car body [2], and a system was presented by Hernández et al. that automatically designs distribution transformers using FEM automatically [3]. The design process of different jet engine components has also been the subject for design automation using KBE (or KEE) integrated with FEA [4, 5]. Stolt developed methods to automatically develop FEM-models for die-cast components [6] and Sandberg, et al. presented a CAD/FEA integration to simulate distortion effects of different manufacturing methods [7]. None of these papers deals with problems where structured meshes are demanded.

The method presented in this paper is described along with a prototype system where the SolidWorks CAD-system has been connected to the ANSA pre-processor to generate FEA-models, which in turn is solved by the LS-Dyna solver. The target is the automation of crash simulations of ski-racks.

Main Idea
The connection between the CAD system and the pre-processor is based on 1) a neutral CAD-file, 2) named CAD-features, 3) a custom object-model, and 4) generic script files.

The main idea is to let the FEA-specialists make geometrical features in the CAD-models that represent the idealizations in the final FEA-model. These features (or bodies) can be points, curves, surfaces, or volumes and are named using a name convention. In the example system, all such names begins with “FEM_” followed by a type declaration and additional information, see Tab. 1. These features serve as the base for the mesh-model.

To have a complete FEA-model also constraints, loads, and other definitions has to be done by the FEA-experts. In the prototype system, this is done using a custom add-in to the SolidWorks-system and results in a collection of “Definition” objects (see Fig. 1). The benefit of making the specifications of the simulation within the CAD-system is that connections, such as contacts and joints, can be added interactively with the CAD-model and that changes of the CAD-model then can be propagated to the FEA-model.

When the CAD-model is prepared with the idealization features and the specifications of the simulation are done, the system is ready to run. The first step done by the system is then to scan the CAD model-tree in order to collect all idealization features. In this step, a collection of MeshPart objects (see Fig. 2) is developed containing information of all the different idealization features and a connection to the real CAD-feature object. While scanning the CAD-model tree, features not being idealization features are hidden away in order to subsequently export an iges-file containing only the geometry to mesh.

A collection of MeshPart objects now exists in the system. It is used to generate a script file to be executed by the pre-processor. The script is generated by replacing parameters in a script-template, and by multiplying some scripting-code specific for different MeshParts. For instance, a revolved mesh is generated in two steps: first the cross sectional surface is meshed and subsequently it is revolved about its axis of revolution defined in the MeshPart originating from the CAD-model.

Code to generate the specifications of the simulation is finally added to the script file. This step might include adding additional nodes and connecting them, adding material definitions, constraints, and contact conditions.
When the script finally is ready, it is submitted together with meshing parameters to the pre-processor in batch-mode to generate the complete FEA-model. The FEA-specialists might open the model to examine the result before submitting it to the solver, or (after the system has been verified enough) automatically submit the result to the solver.

**Conclusion**

When running the prototype system FEA-models are generated in less than 4 minutes compared to up to a week when done manually. This increases the amount of tested product proposals ultimately increasing the product quality without increasing product cost.

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<tr>
<th>Feature Name</th>
<th>Resulting mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM_SURFACE</td>
<td>A meshed surface</td>
</tr>
<tr>
<td>FEM OFFSET_2</td>
<td>A meshed surface that is subsequently offset by 2 mm</td>
</tr>
<tr>
<td>FEM_REVOLVED_360_Axis1</td>
<td>A meshed surface that is subsequently revolved 360 deg about Axis1</td>
</tr>
<tr>
<td>FEM_BEAM_1</td>
<td>Creates a beam of radius 1 mm from a curve</td>
</tr>
</tbody>
</table>

Tab. 1: The name convention used in the example prototype.

**Fig. 1:** The “Definition” class and some of its descendants.

**Fig. 2:** The “MeshPart” class and its descendants.

**References**


Extended Abstract 79

Title
Iterative Sampling for Flatness Inspection Using High Density Data Points

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Keywords
Coordinate Metrology, Inspection, Minimum Zone Evaluation, Adaptive Sampling, Flatness, Convex Hull, Computational Geometry

Introduction
The examination of components with specified geometric and form tolerances requires acquisition of numerous measured data points and extensive computation. Traditionally, the required computation and the software analyses are performed in three major sequential tasks. The first task is to develop a data sampling plan. The sampling plan needs to be developed based on the workpiece characteristics and also type of the employed measurement equipment. The number and locations of surface measurement points are amongst the most important parameters that influence the accuracy and validation of the whole assessment process. However, optimum determination of these parameters is often a difficult and challenging process and no standard procedure or guideline has been developed for it yet.

Next, conformance of the actual geometry to the desired tolerances is evaluated by fitting a substitute geometry to the data points captured by a Coordinate Measuring Machine (CMM).

The third task is to calculate the geometrical deviations associated with the measured part. This task needs to be conducted based on the deviations of the data points from the best substitute geometry and to estimate the uncertainty of the assessed inspection results. Numerous research projects in the area of evaluating the geometric deviations based on the discrete measured points have been undertaken. However, the partitioning of these three key tasks is the prevailing theme in most of the reported approaches. Alternatively, these three tasks can be performed concurrently with continuous feedbacks or as the elements of a closed-loop. This integration and communication between the different modules enhances the level of the certainty, which results in more reliable decisions made by each individual task. In a closed-loop system, an estimation of the form and nature of the geometric deviations can be used to acquire the most useful data-set from the part. Knowing the characteristics of this data-set improves the estimation of the optimum substitute geometry and reduces the corresponding computation cost.

This paper discusses how a loop between the three computational tasks described above can be established to reduce the inspection uncertainty for flatness evaluation. A Convex-Hull approach is adapted to evaluate exact Minimum Deviation Zone (MDZ) of the captured data points. Without being concerned of the possible uncertainties due to the fitting process, an examination platform is developed to purely study the effect of iterative sampling on the accuracy and uncertainty of the inspection evaluation. Using the convex-hull properties in evaluation of MDZ enabled us to utilize a Dynamic Minimum Deviation Zone (DMDZ) evaluation approach. DMDZ evaluation allows a loop between the first the computational tasks, i.e., sampling, fitting processes, and calculation of geometric deviations. By conducting statistical analyses on the experimental observations interesting results are achieved that demonstrate the level of reliability of traditional coordinate metrology processes in inspection of the ordinary manufactured parts and surfaces.

Methodology
The concept of an integrated inspection system is implemented for inspection of sculptured surfaces [1]. An integrated inspection system is developed based on the iterative search procedure and online least square estimation of geometric deviations. A pattern recognition technique called Parzen Windows is utilized for this purpose. Studying the second order discontinuities of the density function of geometric deviations identifies the critical portions of the surface that require further measurement. The current paper presents an extension of this approach which focuses on the on-line estimation of MDZ and studies the effect of the proposed integration on the uncertainty of the MDZ evaluation.

A typical manufactured flat surface with overall dimensions of 330 mm by 150 mm was measured by a CMM equipped with a laser scanning probe. Total of 148,772 data points are measured from the entire surface using stratified sampling. Considering the significant number of data points, the detailed information of the measure surface could be generated. However, the computational time for MDZ evaluation of this amount of data is highly expensive and it is not practical for industrial application.

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
In typical applications usually a much smaller set of data points are randomly selected from the measured surface. However, reducing the amount of data can be interpreted as increasing uncertainty of the inspection process. In order to study the significance of this source of uncertainty an algorithmic approach is used that gradually sample new points from the measured surface to reduce the inspection uncertainty. The sampling processes are virtually conducted by sampling from the original data points measured from the part’s surface. Very high density of the original data points allows us to assume almost data of any small neighbourhood of surface points are available for virtual sampling.

The MDZ is evaluated using the adopted convex hull approach. At the end, the DMDZ procedure is used to develop the convex hull of the entire measured data points. The last result is used to understand the real pattern of geometric deviations on the measured surface (Figure 1) and as the base to study the measuring effectiveness of the small-sized sampling approaches.

![Figure 1: Geometric form details of the inspected surface with 10X magnification](image)

**Conclusion**

Utilizing dynamic minimum deviation zone evaluation practiced in this paper is an approach in developing closed-loops between the computational tasks required for fitting the optimum geometry to the data points and the adaptive sampling strategy, when the adaptive sampling process dynamically updates the data sets to enhance or examine the certainty of evaluated MDZ. By analytical and statistical analyses of the results, it is shown that significant improvements in the accuracy of the entire evaluation process and certainty of the inspection are achieved. Although the integrated model can be used for different applications in coordinate metrology, the results emphasize that in the case of MDZ evaluation, using an adaptive sampling plan is beneficial.

**References**

Extended Abstract 80

Title
A Feature-Based Method to Reconstruct 3D Models from sketches of Mechanical Parts

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Keywords
Sketch, line drawing, reconstruction, feature-based, primitive, 3D model

Introduction
The automatic reconstruction of a 3D object from a single 2D line drawing as a sketch has been very crucial research area since decades for CAD systems, especially in the conceptual design of mechanical products. For the reconstruction, firstly, the connectivity of line segments were defined as junctions such as Y-type junction and L-type junction, e.g.[1]. Each junction could be recognized as convex or concave corner of a 3D object in the sketch, and each line segment could be labeled as plus, minus or arrow. As the result, all of line segments could be labeled uniquely and the 3D model of the sketch could be obtained. This process was named line labeling technique. The sketches of many types of polyhedrons could be reconstructed to 3D models by using line labeling technique.

However, when curved lines are increased in a sketch, the reconstruction becomes difficult by using line labeling technique. Since there are too many kinds of junctions among curved and straight line segments, it is difficult to generalize curved line labeling. Although several approaches exist for curved line labeling, e.g.[2],[5], it is difficult to recognize a hole in Example 1 illustrated in Fig. 1(a) because the hole can be recognized as a part of convex spheres. Humanized recognition would be required for reconstructing a 3D hole from the sketch of hole in Example 1.

In the method of this paper, primitives and features are extracted repeatedly from sketches of mechanical parts. This process is similar to the reverse process of solid modeling in 3D CAD and the method can be a feature-based method. The 3D models of the sketches would be reconstructed by composing the solid models of extracted primitives and features in the method. An important merit of the method is that it is easy to handle holes and fillets in the sketches for the reconstruction. Although Wang et al. [4-5] applied extracting primitives for the reconstruction, they did not handle features. Feasibility studies of the method have been performed in various kinds of sketches of mechanical parts. So the algorithm and the limitation of the method are explained in detail in this paper.

Main Idea
In the present step, cube and cylinder are applied as primitives, and hole and fillet are applied as features in the method of this paper. The objects of sketches are limited to simple mechanical parts that can be made by drilling and milling. This limitation corresponds to the primitives and features of the method. The outline of algorithm of the method is as follows.
(1) Input a sketch drawn in 2D CAD into the method.
(2) Recognize each of line segments and faces in the sketch.
(3) Recognize a primitive or a feature in the sketch.
(4) Extract it from the sketch and its 3D model are made.
(5) If there are broken line segments in the sketch, they would be restored by stretching themselves as in [3].
(6) Repeat processes from (3) to (5) until any line segments do not exist in the sketch.
(7) Compose all of 3D primitives and/or features to obtain the 3D model of the sketch.

Since 3D objects drawn as sketches are mechanical parts that are made by drilling and milling, for example, pyramids are not 3D objects in the method. The ways of recognizing cube, cylinder, hole and fillet from sketches are defined as follows. Also, the 3D objects are viewed in some general view.

[CUBE] (1) There are two or three parallelograms connecting to each other.
(2) Their connecting lines form a Y-type junction.
(3) If there are two parallelograms, one additional line can be added to make three parallelograms.

[CYLINDER] (1) There are an ellipse, an arc and two parallel straight line segments contacting to them tangentially.
(2) These lines form a closed loop of lines.

[HOLE] (1) There are an ellipse and an arc, and the arc is a part of the ellipse.
(2) The arc is placed in the inside of the ellipse and they are connected to each other.
(3) The ellipse is placed in the inside of some other face.

[FILLET] (1) There are two or more arcs whose radiuses are the same and they are placed in parallel.
(2) One of the arcs is tangent to two straight line segments.
(3) A corner can be made by extending and adding straight line segments.

The process of reconstruction of Example 1 in the method is explained as follows. Firstly a hole can be recognized and colored red as in Fig. 1(b). In this figure, the hidden lines of the hole can be drawn and colored green. The recognition of a cylinder is the same as a hole. When the hole is extracted from Example 1, its sketch is changed into Fig. 1(c). In this figure, there are three arcs and straight lines, and they can form a fillet and are colored red. When the straight lines are extended, a corner is made by adding a green line segment as in Fig. 1(d). In the same way two corners are made as in Fig 1(e). In Fig. 1(f), two fillets are recognized and colored red. In these fillets, the arc connecting to two straight lines forms a corner preferentially as in Fig. 1(g). Finally two cubes can be recognized and extracted as in Fig. 1(h). The solution as the 3D model of Example 1 can be obtained by composing extracted cubes, fillets and the hole. Fig. 1(i) illustrates the overviews of the solution.

Fig. 1: The reconstruction of Example 1: (a) Example 1, (b) Recognition of a hole, (c) Recognition of two fillets, (d) Generation of a corner from (c), (e) Generation of two corners, (f) Recognition of two fillets, (g) Generation of two corners from (f), (h) Recognition of two cubes, (i) The overviews of the solution.

Conclusions

In this paper, a feature-based method of automatically reconstructing 3D models from 2D line drawings as sketches is proposed. In the present step, cube and cylinder are applied as primitives, and hole and fillet are applied as features in the method. The process of recognizing and extracting primitives and features from sketches are explained in Example 1. Especially the recognition of various kinds of fillets is applied in the method. So sketches including many curves could be applied by the method in mechanical parts made by drilling and milling.

References

Extended Abstract 81

Title
Effective Collaboration through Multi-user CAx by Implementing New Methods of Product Specification and Management

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Keywords
Multi-user CAx, collaboration, design process, specification gathering, task decomposition, task distribution

Introduction
While success of a designed product can be measured in a variety of ways, the three most commonly accepted success metrics are: cost, performance, and completion time [2]. But these metrics are rarely independent of each other; rather, they are most always in direct competition. Design and manufacturing dependencies normally complicate the product design process, due in part to administrative structures that separate personnel by expertise and function. For example, when making improvements to a product’s functionality or performance, costs often increase due to additional manufacturing processes, or related tooling or a more rigorous design process designed for serial interactions among the product design personnel.

In the last two decades focus has shifted to methods for improved concurrent engineering and collaboration. Recent research into multi-user Computer-Aided Application (CAx) tools like CAD/CAE/CAM has provided preliminary prototypes where multiple designers enter and work in the same design space simultaneously [3][4]. These researchers, by allowing multiple users to work in parallel on the same model, have demonstrated that design completion time can improve, at least at the session level, in proportion to the number of users in the same session. This paper addresses a research issue that has thus far been neglected: How will these advanced multi-user software tools be administered?

How might existing processes and organizations take advantage of new CAx tools that will permit multi-users in a design space/model simultaneously? How would organizational and management structures or the process steps used to manage product development effect training methods, or training materials, or the set of applications that a company installs? How would simultaneous collaboration affect the management of product related databases, and networks, or personnel hiring, or supplier selection?

Main Idea
Engineering designs are increasingly complex, requiring distributed designers and stakeholders of varying expertise to converge a solution for a complex and extensive set of design specifications. The interdependent relationships within the specifications make it impossible to converge to reasonable solutions without collaborative compromise between the distributed designers, many of whom have differing cultural backgrounds. Designers must be able to communicate effectively the rationale behind their design decisions, and understand the rationale of the other designers to make the most beneficial compromises [5].

An in-depth study was performed with the focus of implementing multi-user design principles within a new collaborative administrative structure. As a result of this study, tools were developed that would be of benefit to a multi-user managerial approach, shown in the Figure 1 sequence. A new area of design process improvement was also discovered. A large percentage of all design time is taken up by iteration cycles. These iteration cycles are inherent in any design, as tradeoffs must be made between basic design requirements. However, the detrimental effect of iterative cycles is compounded by the serial nature of product design and the lack of collaboration during product design. By applying new research into multi-user CAx applications, and providing a framework to manage the users within the design sessions, the main issues associated with design iterations can be minimized, and more effective design and collaboration achieved.

Effective collaboration focused project management begins at the early stages of the design process. As design specifications are gathered and defined, independent relationships begin to emerge. Tools such as the House of Quality (HOQ) have commonly used to help with the specification definition phase. A lesser utilized portion of the HOQ tool is located in the roof of the house, and provides an opportunity to rate specification interdependencies [1]. A Specification Rating Matrix (SRM) matrix has been defined using the roof of the house of quality as its model, to collect and store specification relationship data. By taking advantage of this correlation data at the lowest levels, information regarding likely future iterations are identified and stored for later use.
Later in the design process, the project is decomposed onto separate tasks each of which addresses a number of the design specifications previously defined. A Design Structure Matrix (DSM) is utilized to determine relationships between tasks. These relationships have been leveraged in prior research to determine task sequence and opportunities for parallel completion [6]. This research utilizes the information gathered in the SRM to populate the DSM and provide insight into the relationships between each task derived from the specifications addressed by the task.

![Figure 1: Example DSM, SRM, and optimal Task Sequence](image)

By utilizing the relationship data, as well as information on the required decision makers to address each task, an optimal task sequence is generated as well as the needed expertise required in a design team to perform the set of tasks. This team can then be placed within the same collaborative design environment, and organized to perform the tasks in the prescribed manner. This allows the required expertise to be present during design, with the necessary experiences to participate fully in each decision. When design conflicts arise between specifications or tasks, each user can fully collaborate and arrive at a suitable compromise much quicker. Design rationale is freely shared between designers, and improved design is achieved utilizing the collective intelligence of the group.

To test this method a simulation was created to simulate a complex design; see Figure 2. Two approaches to the design were taken: an iteration cycle between multiple designers working with single user tools, and a group of similar designers with defined roles working in a collaborative design environment.

![Figure 2: Sample Test Trials, Left: iterative approach, Right: multi-user approach](image)

Conclusions
The results from the test show a significant improvement in overall design, as well as reduced design time in each of the multi-user trials over the iterative design method. Users were able to freely communicate and help each other with the design. Through these tests, we demonstrated the effectiveness of a carefully defined design team, with multi-user organized specifications for a collaborative environment, and that, through this method, improvements can be made to product performance, as well as design time.

References
**Extended Abstract 82**

**Title**
Adaptive Slicing Approach to Control Surface Error in Rapid Prototyping Process

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**Introduction**

In Rapid prototyping (RP) manufacturing part is manufactured using layer by layer addition of material from a Computer Aided Design (CAD) model. Traditionally the CAD model is transferred to RP system after exchanging to STL format which is triangulated tessellation of the CAD model. Then it is sliced using different slice algorithms and machine constraints. The inherent uncertainties in this process have led to development of adaptive slicing technique. There are several adaptive slicing techniques but only few researches have been done to calculate an actual surface error factor and the cost aspect of the slicing algorithm. This paper proposes new adaptive algorithm to compute a surface error factor and to find the cost effective approach for slicing. The adaptive slicing algorithm dynamically calculates slice thickness and it is based on the allowable threshold for error to optimize the cost and time. The paper also provides comparative study of previously developed adaptive models by the authors based on cusp height [1] and surface derivative [2].

**Main Idea**

The current study proposes an adaptive slicing algorithm to reduce cost and surface error. Central to the problem of slicing CAD model is the determination of intersection points between the slicing plane and the model. The developed algorithm receives IGES form of the CAD data as input instead of the STL file. First, a solid or surface mode of multi-feature CAD part is converted to IGES format to be exchanged to the developed computational platform. The developed computational program reads through IGES file and converts the IGES file into an executable customized database based on the geometric features such as Line, Curve, B-spline curves, B-spline surface, NURBS, point etc. Then the data parameters of IGES file are divided into three categories of points, curves and surfaces. Maximum Z point ($Z_{max}$) and minimum Z point ($Z_{min}$) is computed for slicing algorithm from this data. The IGES file is plotted based on the geometric features in the CAD file. If any feature entered to the computational system represented by, $G$. Then $G$ can be expressed as:

$$ G = S_{n} \cup S_{r} \cup S_{s} $$

where $S_{n}$ represents the NURBS surfaces, $S_{r}$ is Planer surfaces, and $S_{s}$ is reevaluated and trimmed surface. For $S_{n}$ the cloud of data is computed based on linear interpolation. $S_{r}$ is converted to $S_{n}$. $S_{n}$ NURBS curves $C$, and point clouds are computed base on NURBS Equation [3]. First order derivative of $S_{p}$ is the NURBS curve and $S_{n}$ is also computed from based on the NURBS equation [3]. For the process of adaptive slicing, first the CAD model is sliced once with maximum layer thickness and once with the minimum layer thickness. Average error for each layer is computed for both cases and saved as maximum allowable average error $E_{\text{max-avg}}$ and minimum allowable average error $E_{\text{min-avg}}$ as described in the following Section. For the consecutive slicing process the surface error factor is computed based on considering the 20 points belong to two consecutive surfaces. For each pair of points ($P_{i}$ and $P_{i+1}$) in the consecutive slices the surface error $e_{p}$ is computed for 10 different points along the profile Curve. The error factor, $e_{p}$, for $P_{i} - P_{i+1}$ patch is calculated as follows.

$$ e_{p} = \sum_{i=1}^{10} \min(h_{v}^{i}, h_{h}^{i}) $$

where $h_{v}$ and $h_{h}$ are the Euclidian distances to the vertical and horizontal plane (Figure 1).

![Fig. 1: Surface Error Calculation](image)

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*International CAD Conference and Exhibition, Final Program CAD’13 Volume 10*
The total error at the j-th slice $e_j$ is

$$e_j = \sum_{i=1}^{N} e_{ij}$$

where $e_{ij}$ is the error of the individual j-th point number. The total error, $E_{total}$, for entire part is computed from following equation.

$$E_{total} = \sum_{i=1}^{N} e_j$$

where, $n$ is the total number of slice. Average error $E_{avg}$ for the slice is calculated from the equation.

$$E_{avg} = \frac{\sum_{i=1}^{n} e_{i}}{n}$$

In order to compute adaptive slicing heights the evaluation algorithm starts with by taking $Z_j$ as $Z_{min}$ and maximum possible slice thickness $t_{max}$ as the current slice thickness, $t_c$. Assume that we have $n$ number of layers with layer thickness $t_n$ where $i = 1, 2...n$. Then, $Z_j$ is computed form Equation 6.

$$Z_j = \sum_{i=0}^{n} t_i; j \leq m$$

For i-th $Z_j$ height point on the CAD surface number of $PZ_i$ points are computed considering the intersection between plane $S_P$ at $Z_j$ and the CAD surface, $G$. The NURBS intersection points are computed using the algorithm developed by Barnhill & Kersey [4]. For the consecutive slicing the surface error $e_{ij}$ is computed by considering the 20 points on the two consecutive surfaces as described by using Equations 2 and 3. This $e_{ij}$ value is then compared with Error threshold value $E_{allowable}$ which is computed using Equation 7.

$$E_{allowable} = \frac{a}{100} E_{min - avg} + (1 - \frac{a}{100}) E_{max - avg}$$

In Equation 7, parameter $a$ is user defined threshold factor to control the desired error. As described, if $e_{ij}$ is greater than $E_{allowable}$ then the procedure is repeated with new $t_j$ which is the next possible slicing height based on the machine specification. Otherwise, height is saved and the computation of the next slice height begins. This process runs till $Z_j$ is smaller than the maximum CAD height in the Z-direction.

**Conclusion**

A new adaptive direct slicing algorithm of CAD models based on a surface error factor is implemented for several test cases and compared with previously developed algorithm for accuracy. Comparing the results of implementation with the common practice for several case studies shows that the proposed approach has greater slicing efficiency.

**Acknowledgements**

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**References**


Extended Abstract 83

Title
Shape Analysis of Cubic Bézier Curves – Correspondence to Four Primitive Cubics

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Keywords
Moving Line, Double Point, Crunode, Cusp, Acnode, Inflection Point

Introduction
In this paper, we show that any planar polynomial cubic Bézier curve can be described as an affine transformation of a part of four primitive cubics \( x^3 + x^2 - 3y^2 = 0, \quad x^3 - 3y^2 = 0, \quad 3x^2 - 3y^2 = 0, \quad x^3 - y^3 = 0 \).

For highly aesthetic curve design, properties of curvature change, such as monotonicity and logarithmic curvature graph [1], are important. Curvature monotonicity of cubic Bézier curves has been studied [2], however, the results are complicated. It is because relationship between Bézier control points and curvature properties are mainly focused.

In our project, we try to investigate the curvature properties for the whole set of polynomial cubics. Here, the whole set consists of four primitive cubics listed above with affine transformation, i.e., the curvature properties of polynomial cubic curves can be completely surveyed by investigation of each primitive and its scaling and skewing. In this paper, as the preparation of the project, we clarify the correspondence between Bézier curves and the primitive cubics. In addition to conventional shape classification (self intersection, cusp, inflection point, etc.) of cubics [3], we show that the whole set of cubic Bézier curves is equivalent to the four primitive cubics and their affine transformation, which is our main contribution.

Definitions
In this research, most part of the theory is based on moving line (family of lines on Bernstein basis) [4]. Here are some definitions and properties of point, line, Bézier curve, and moving line in 2D homogeneous coordinate.

- Point: \( P = (X, Y, W) = w(x, y, 1) \)
- Line: \( L = (a, b, c) : aX + bY + cW = 0 \)
- Point \( P \) lies on line \( L : P \cdot L = 0 \)
- Line \( L \) contains two points: \( L = P_0 \times P_1 \)
- Point \( P \) is the intersection of two lines: \( P = L_0 \times L_1 \)

- Bézier curve with control points \( P_i : P(t) = \sum_{i=0}^{n} B^n_i(t)P_i \) where \( B^n_i(t) = \binom{n}{i}(1-t)^{n-i}t^i \)
- Moving line with control lines \( L_i : L(t) = \sum_{i=0}^{n} B^n_i(t)L_i \)
- Curve follows moving line (or moving line follows curve): \( P(t) \cdot L(t) = 0 \)
- Moving line follows two curves: \( L(t) = P_0(t) \times P_1(t) \)
- Curve is the intersection of two moving lines: \( P(t) = L_0(t) \times L_1(t) \)

Main Idea
Here, for given control points \( P_i \) of a polynomial cubic Bézier curve, we derive linear moving line \( L_d(t) \) and quadratic parallel moving line \( L_d(t) \) both of which follow the Bézier curve. Then, we classify the curve to specify the appropriate primitive, and find three reference points \( D \) (or \( I \)), \( E \) (or \( G \)), \( F \), from which the affine transformation matrix \( M \) can be obtained.

**Double Point** and **Linear Moving Line** \( L_d(t) \)

For cubic Bézier curve \( P(t) = (1-t)^3P_0 + 3(1-t)^2tP_1 + 3(1-t)t^2P_2 + t^3P_3 \), if it cannot be expressed in lower degree, moving line \( L_d(t) \) that goes through a fixed point on the curve \( P(t) \) and follows the curve \( P(t) \) can be represented:

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
\[ L(t) = P(t) \times P(t) = (t - \tau) \left( (1 - \tau)^2 (1 - \tau) \tau^2 \right) \begin{bmatrix} Q_0 \times Q_1 & Q_0 \times Q_2 & Q_0 \times Q_1 \\ Q_0 \times Q_1 & Q_0 \times Q_1 & Q_0 \times Q_1 \\ Q_0 \times Q_1 & Q_0 \times Q_1 & Q_0 \times Q_1 \end{bmatrix} \begin{bmatrix} (1 - \tau)^2 \\ (1 - \tau) \tau \\ \tau^2 \end{bmatrix} \]

where
\[ \begin{align*}
Q_0 &= P_0 \\
Q_1 &= 3P_1 \\
Q_2 &= 3P_2 \\
Q_3 &= P_3.
\end{align*} \]

Although this \( L(t) \) is quadratic in general, it becomes linear when \( P(\tau) \) is the double point of the curve \([4]\).

Such linear moving line \( L_0(t) \) can be obtained by
\[ L_0(t) = (1 - t) L_{00} + t L_{01} \]

\[ \begin{cases}
L_{00} = V_{023}(Q_0 \times Q_2) - V_{013}(Q_0 \times Q_1) + V_{012}(Q_1 \times Q_2) \\
L_{01} = V_{023}(Q_0 \times Q_1) - V_{013}(Q_0 \times Q_2) + V_{012}(Q_1 \times Q_2)
\end{cases} \]

where \( V_{ijk} = Q_j \cdot (Q_i \times Q_k) \).

The double point \( D \) of the curve is \( D = L_{00} \times L_{01} = w_p(x_D, y_D, 1) \)

**Quadratic Parallel Moving Line \( L_1(t) \) and Its Existence Area**

If \( D \) is not at infinity, quadratic parallel moving line \( L_1(t) \) that follows the curve \( P(t) \) can be derived by setting \( \tau = \infty \):
\[ L_1(t) = (1 - t)^2 L_{10} + 2(1 - t) t L_{11} + t^2 L_{12} \]

\[ \begin{cases}
L_{10} = (-Q_0 \times Q_1 + Q_0 \times Q_2 - Q_2 \times Q_0) = (a_{10}, b_{10}, c_{10}) \\
L_{11} = (1/2)(-Q_0 \times Q_1 + Q_0 \times Q_2 + Q_1 \times Q_2) = (a_{11}, b_{11}, c_{11}) \\
L_{12} = (-Q_0 \times Q_1 + Q_0 \times Q_2 - Q_2 \times Q_1) = (a_{12}, b_{12}, c_{12})
\end{cases} \]

This moving line \( L_1(t) \) moves in parallel, and exists in a certain half plane, whose border line \( L_1(t_E) \) can be obtained by:
\[ L_1(t_E) = 0 \quad \ldots t_E = (c_{10} - c_{11})/(c_{10} - 2c_{11} + c_{12}) \]

The curve tangents to the border line at the point \( E : E = L_0(t_E) \times L_1(t_E) = w_p(x_E, y_E, 1) \)

**Classification, Reference Points, and Affine Transformation from Primitive Cubic**

Let \( f(t) = L_1(t) \cdot D \), and let \( D \) be the discriminant of quadratic equation \( f(t) = 0 \).

**Case 1: Crunode --- If \( D > 0 \)**

Let \( t_F \) be the greater root of \( f(t) = 0 \) and calculate \( F = L_0(t_F) \times L_1(t_F) = w_p(x_F, y_F, 1) \). Curve \( P(t) \) is equivalent to the following primitive cubic with affine transformation \( M \):
\[ \begin{align*}
x &= \tilde{t}^2 - 1 \\
y &= \frac{1}{\sqrt{3}} \tilde{t}^3 \\
x^3 + x^2 - 3y^2 &= 0
\end{align*} \]

\[ \tilde{t} \in [t_E, t_F] \]

\[ M = \begin{bmatrix}
x_D - x_E & y_D - y_E & 0 \\
x_E - x_D & 0 & y_D - y_E \\
0 & y_D & 0
\end{bmatrix} \]

**Case 2: Cusp --- If \( D = 0 \)**

Let \( t_F = t_E + 1, F = L_0(t_F) \times L_1(t_F) = w_p(x_F, y_F, 1), G = L_0(t_E) \times L_1(t_E) = w_p(x_G, y_G, 1) \). Curve \( P(t) \) is equivalent to the following primitive cubic with affine transformation \( M \):
\[ \begin{align*}
x &= \tilde{t}^2 \\
y &= \frac{1}{\sqrt{3}} \tilde{t}^3 - 1 \\
x^3 - 3y^2 &= 0
\end{align*} \]

\[ \tilde{t} \in [-t_E, -1] \]

\[ M = \begin{bmatrix}
x_G - x_D & y_G - y_D & 0 \\
x_D - x_G & 0 & y_G - y_D \\
0 & y_D & 0
\end{bmatrix} \]

**Case 3: Acnode --- If \( D < 0 \)**

Let \( G = (2x_D - x_E, 2y_E - y_D, 1) \). Let \( t_F \) be the greater root of \( L_0(t) \cdot G = 0 \), and \( F = L_0(t_F) \times L_1(t_F) = w_p(x_F, y_F, 1) \). Curve \( P(t) \) is equivalent to the following primitive cubic with affine transformation \( M \):
\[ \begin{align*}
x &= \tilde{t}^2 + 1 \\
y &= \frac{1}{\sqrt{3}} \tilde{t}^3 + 1 \\
x^3 - x^2 - 3y^2 &= 0
\end{align*} \]

\[ \tilde{t} \in [-t_E, -1] \]

\[ M = \begin{bmatrix}
(1/2)x_G - x_D & (1/2)y_G - y_D & 0 \\
(1/2)x_D - x_G & 0 & (1/2)y_G - y_D \\
0 & y_D & 0
\end{bmatrix} \]

**Case 4: Explicit Cubic --- If \( D \) is at infinity**

Curve \( P(t) \) is equivalent to the following primitive cubic with an affine transformation:
\[ \begin{align*}
x &= \tilde{t} \\
y &= \tilde{t}^3 \\
x^3 - y &= 0
\end{align*} \] (Results are omitted because of space limitation.)
Conclusion
We have clarified the correspondence between polynomial cubic Bézier and the four primitive cubics. Based on this fact, we will advance the curvature analysis of the primitive cubics and their affine transformation.

Fig. 1: Bézier and primitive cubic (with crunode). Red triangles show the correspondence.

Fig. 2: Bézier and primitive cubic (with cusp).

Fig. 3: Bézier and primitive cubic (with acnode).

Fig. 4: Bézier and primitive cubic (explicit cubic).

References
Extended Abstract 84

Title
An integration of ECO-DESIGN guidelines based on structural optimization in a CAD framework

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Keywords
Eco Design, CAD, structural optimization, LCA

Introduction
During previous decades, engineers were only concerned about designing products that met given requirements and paying little attention to the future availability of natural resources. Current design trend is changing; in fact the product has to fulfill either functional performances or market needs and to ensure the maximum added-value with minimum resources, such as the minimal material and/or energy wastage.

To achieve this goal, many eco-design tools (in form of guidelines, checklists and analytical tools) have been conceived to identify where it is more useful to intervene, and how to improve current products and processes [1-3]. While suggesting how to modify a product in order to improve its environmental performances, these methods fail to provide a direct link with an active LCA assessment module. Therefore, it is difficult to assess whether a certain design choice represents a right direction of intervention and results in favourable influence on the overall environmental impact of the product unless one lands up making a new LCA.

Main Idea
This paper refers to this context and pays a particular attention to ECO-design tools adopting a LCA approach integrated within a CAD environment. They have been analyzed through an evolutionary perspective in order to highlight the promising developments and their intrinsic limits.

To overcome identified limits, an innovative approach is proposed: a systematic eco-sustainable computer aided design procedure based on the integrated management of (1) virtual prototyping tools (e.g., CAD 3D, FEA, structural optimization), (2) function modeling methodology, and (3) LCA tools. The core of the method is mainly based on the configuration of structural optimization strategies specifically conceived to obtain lighter and more compact products, and therefore, more eco-sustainable. The objective of the proposed methodology is to support the designer in choosing the best triad shapematerial-production in order to determine the minimum environmental impact ensuring the specific structural and functional requirements of the product. At present the proposed system works with the minimum set of parameters, which could be updated with many additional ones. Thanks to the integration of mentioned computer-aided tools, the designer becomes aware of the consequences that each design modification (to the geometry, the material or the manufacturing process) determines on the environmental impact of the product along its life-cycle, allowing better results of those suggested by whatever “design for X”.

To redesign a product, the user first sets the functional and structural requirements (by defining loads configurations and constraints), and chooses suitable materials and manufacturing processes from predefined libraries. Then a structural optimization tool, by adopting our optimization strategies, automatically produces different and eco-oriented variants of the initial product. For each variant, an environmental assessment to visualize in real time its sustainability is also automatically produced. The article shows how to articulate the workflow between virtual prototyping and LCA tools as a foundation for an innovative computer aided ECO-design tool to help industrial sector to design more sustainable products in a more efficient way. The methodology has been experimented with different case studies; the case study of moped rim will be described to explain the overall procedure.
Conclusions
In this paper we propose a design process able to support the designer during the environmentally sustainable redesign of any product that can be modeled in CAD field. The work lays the foundations for an eco-design path integrating CAE and LCA tools. The procedure allows the designer to take the most strategic decisions without verify ex post the goodness of his/her intuition or rely on generic green design best practices, so overcoming the limits of a classic design process such as “Design for X”.

References
Extended Abstract 85

Title
Reconstruction of 3D geometry of general curved surfaces from a single image

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Keywords
3D Reconstruction, Reverse Engineering, Freeform Surface

Introduction
Construction of 3D model from 2D images is important in reverse engineering and inspection applications. 3D reconstruction from a single 2D image is an ill posed problem, since information about the true depth of a scene point is lost in the 2D projection. Existing algorithms to solve such problems demand presence of reference entities (line, plane) and a variety of geometrical cues that can be easily recognized [1]. These entities or cues simplify the problem of camera calibration [6]. The reconstruction problem is straight-forward if the camera is calibrated.

Criminisi et al. [2] proposed an approach for single view metrology, and showed that affine scene structure can be recovered from a single uncalibrated image. This approach requires three mutually orthogonal vanishing points to be available simultaneously in the image plane. Thereafter, in order to recover the metric measurements they require three reference distances. Once the affine structure is recovered, it is possible to use techniques used to inflate sketches. Cubic corner technique has been used in the literature for obtaining the third dimension from polyhedral sketches drawn in parallel projection [4]. This technique is effective for regular polyhedra whose planes are all mutually perpendicular. Lee et al. have extended this approach for the reconstruction of certain category of freeform shapes from a line drawing capturing the shape in parallel projection [5].

Main Idea
In this paper a novel method is proposed which combines the technique of recovering affine scene structure without requiring camera calibration, and the cubic corner method to extract 3D geometry from the image of a free-form surface. Input is a single image of a surface (that could be a face in a three dimensional object). At first projective distortion is removed and similarity geometry is established using the boundary curve chord’s characteristics. The scale information that is lost in the single image is supplied as a chord length. Then control grid points are generated. Cubic corner method is applied to the control points as the control points form a polyhedral and therefore more amenable to inflation using cubic corner. This also reduces the number of points to be processed. A construction scheme has been proposed to determine a third point that forms an orthogonal triad to apply the cubic corner method. A B-spline surface is then obtained from the 3D control points.

The assumption of three mutually orthogonal vanishing points required in the literature is relaxed to the assumption that the surface boundary has parallel chords. This reduces the number of vanishing points required to two. The steps are as follows: The input image is first processed using standard edge detection schemes to identify the boundary of the surface. Segmentation scheme is then used to obtain the corners. Chords between the corners identified are then used to find the vanishing points and line. Using these the projective distortion matrix is computed. This is then used to recover the affine structure. Next the absolute points or circular points (that are invariant to similarity transforms) are determined and used to determine the surface boundary in the similarity space. Curve is fitted to the boundary edges and control points obtained. A control point grid for the entire surface patch is obtained by a bilinear Coons patch. The cubic corner scheme is then applied to the control points in order to obtain 3D control points using which the 3D surface is obtained.

A novel approach to apply cubic corner to the 3D control points is described. This approach is able to handle cases where the three points being considered do not form orthogonal vectors by identifying new points that are orthogonal and on the surface.
Fig. 1: Sequence of construction – surface, image with edge detection, determination of vanishing point, similarity transform, control point grid, inflation using cubic corner.

Conclusions
The proposed procedure has been implemented and tested on some surfaces. Chord lengths are taken as cues for conversion from perspective to similarity space and later in full metric three dimensional reconstructions. The error in the third dimension (depending on the view) is within 5%. The error is worst at the ends because of the fact that the third point at the boundary edge is not available for the cubic corner method and is currently forced to some pre-defined value. The advantages of the proposed approach are that no feature extraction is required and the image need have only two vanishing points in orthogonal direction. Only untrimmed surfaces have been addressed here. Ongoing work is exploring the use of intensity data in the interior (in addition to the boundary information presently used) to improve the accuracy of reconstruction and to remove the restriction of parallel chords.

References
Extended Abstract 86

Title
Analyzing Adaptive Expertise and Contextual Exercise in Computer-Aided Design

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Keywords
CAD, Contextual Exercise, Adaptive Expertise

Introduction
Today the Computer-Aided Design (CAD) industries are evolving dramatically: wide varieties of CAD tools are available and they are updated frequently. The fast changing pace of these CAD tools has demanded engineering curricula to educate students to allow their CAD skills to be transferable to other CAD platforms and new versions. Unfortunately most current CAD instructions are focused on teaching declarative knowledge – the key strokes and button picks required to perform certain tasks in specific software platforms [2]. Very limited attentions have been paid to teach students to be more adaptive in using CAD tools. According to a survey conducted by Ye et al. [6] on how industries evaluate the current CAD education in colleges and universities, 74 percent of the participants from the industries indicated that current CAD education is inadequate. Wineburg defines adaptive expertise as: “the ability to apply, adapt, and otherwise stretch knowledge so that it addresses new situations - often situations in which key knowledge is lacking” [5].

To address the deficit of the CAD education, the authors have implemented an Adaptive Expertise Survey (AES) and contextual modeling exercise in a freshman CAD class. This work examines the role of adaptive expertise in CAD modeling and investigates the role of learner-centered contextual exercises on CAD modeling procedures.

Main Idea
The Adaptive Expertise Survey (AES) and contextual modeling exercise were carried out in a freshman CAD course in Mechanical Engineering. The course is a 3-hour laboratory session where the students learn engineering graphics and 3D modeling based on a CAD platform, NX. An Adaptive Expertise Survey developed by Fisher and Peterson [1] was given to the students. The survey includes four main constructs of adaptive expertise: metacognition, goals and beliefs, epistemology, and multiple perspectives. The survey is to assess the students’ beliefs and cognition in relation to the constructs of adaptive expertise.

After the survey, the students were divided into two groups: experimental group and control group. The experimental group constituted a learner-centered and contextual exercise. The students in the experimental group were asked to bring a real-life object of their choice to the classroom. Students measured the dimensions of the object and modeled it in NX during the class. The students in the control group were asked to create a model in NX based on a drawing provided to them. This is similar to a regular exercise that they usually do. Students in both groups were interviewed twice, once before the exercise and once after the exercise. In the interviews, the students were asked a set of questions about their proposed and actual strategies and modeling procedures. The interviews were recorded and then transcribed for qualitative analysis.

All the NX models were analyzed in order to examine the modeling procedures of the students in both control and experimental groups. The attributes of the models were evaluated, including “correct initial sketch plane”, “correct model origin”, “correct base feature”, “number of reference geometry”, “number of segments per feature”, etc. The attributes are based on the authors’ previous work [3], [4]. The students’ pre and post interview transcriptions were coded based on the adaptive expertise dimensions defined by Fisher and Peterson [1].

This paper presents the study findings, which combine the adaptive expertise survey responses, attributes data of NX models, and the before and after interview findings. The statistical relationships among the variables are reported. The comparison of the control and the experimental groups’ data are also presented.
Discussion
The students’ responses to the AES and interviews were analyzed to explore if the students in different demographic groups (i.e., sex, rank, age, 1st generation college students, with/without work experience) possess different adaptive expertise characteristics. The results suggest that female students conveyed more AE characteristics than male students. When the freshman students were compared to junior students, the AES showed that freshman students have more adaptive expertise oriented goals and beliefs than the junior students. However, junior students conveyed more adaptive expertise responses than freshman students in the pre-interview. As expected, when the students were more mature and experienced, their adaptive expertise characteristics were enhanced. In another comparison, non-first-generation college students reported significantly more adaptive expertise characteristics than the first-generation college students. This suggests that the parents’ education levels may correlate with the development of their children’s adaptive expertise.

In the contextual modeling exercise, the NX model attributes of the control group and the experimental group were compared to examine if students use different modeling procedures. The analyses showed that the students completing the contextual exercise used more correct modeling processes and attributes than students completing the regular exercise. The experimental group showed better performance choosing the correct feature sequence, used less incorrect feature terminations, and used more correct base feature, more correct orientation, more reference geometries, and more patterns than the control group. Examining the AES responses and the interview data of the two groups revealed that the adaptive expertise characteristics of the students in two groups were not different from each other. The adaptive expertise can be excluded from the factors causing the differences. It suggests that the contextual exercise has a positive effect on improving students’ CAD modeling procedures.

The correlations were examined between the model attributes and AE responses from survey and interviews. The correlations showed that students with higher adaptive expertise (mainly epistemology sub-dimension) used more reference geometries, more complex features (i.e., feature with more segments), and more pattern features (i.e., instance features in NX). Those features are considered as better modeling strategies to convey design intent as discussed in previous work [3], [4]. These findings show that adaptive expertise especially epistemology sub-dimension is associated with positive effects in CAD modeling. When the correlations were examined individually for the control group and experimental group, the experimental group revealed more significant correlations than the control group. This is an indicator that the contextual exercise is a good way to enhance students’ adaptive expertise on CAD modeling.

Conclusions
This paper presents the findings of a project that is examining the role of adaptive expertise in CAD modeling and investigating the role of a learner-centered and contextual exercise on CAD modeling procedures.

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References
Extended Abstract 87

Title
A Design System for 3D Bending Shape of Flexible Printed Circuit in Electronics Devices

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Keywords
CAD, digital mockup, surface modeling, rectifying developable, flexible film

Introduction
Electromagnetic Interference (EMI) and Compatibility (EMC) are critical properties to be considered in electronics device development. Simulation systems have been extensively used to analyze these properties. We are interested in a problem to generate 3D shape information of components of the electronics device needed for such electromagnetic simulations. Among such components, Flexible Printed Circuits (FPCs) are increasingly being used in small electronics devices such as mobile phones. The FPC is made on a thin film which has wires to transmit signals and electric power, and often includes electronic circuits. As the FPC can be considered non-stretching and non-shrinking in their usual usage state without external forces in the electronics devices, they can be modeled as a developable surface.

A ruled surface is generated by moving a straight line along some curve. The ruled surfaces are classified into developable surfaces and non-developable surfaces. Developable surfaces are extensively studied in computer aided geometric design. For instance, developable surfaces can be modeled as Bézier surfaces [1,3]. However, to our knowledge, little work has been done on generating developable surfaces from a single curve except [2] in which paper bending is studied. Paper is the most typical example of developable surfaces. Representing behavior of paper and its use for modeling have been studied also in other places. Kergosien Y. et al. [7] represented paper shape by its boundary and a mapping between boundary points, and a shape is generated by using simple physical simulation. Thus it is not an intuitive way for designing paper shapes. Frey W. H. [5] proposed a method to design a developable surface from a given closed curve, which is difficult to compute and not intuitive to be used in our problem.

Main Idea
In this paper, we propose a system for designing 3D bending surfaces of FPCs. As shown in Fig. 1, the input is a 2D flat pattern representing a profile of the FPC and its medial line connecting the terminal ends of the FPC. Then the user can design a 3D path of the FPC by modifying a curve corresponding to this medial line. Thus we call this curve control curve of the FPC. Then the developable surface is generated along the control curve. A method of rectifying developable surface [2] is applied to generate the surface with the following extensions to our problem:

1) Boundary conditions for the control curve are defined in such a way that the terminal ends of the FPC must be mounted to specified connectors of circuit boards.
2) During modifications by the designer, the curve length must be preserved. A method is proposed in [2] to modify the parameter range of the curve to give the target length. However, in our case as both end points are fixed, their method cannot be used. A new method based on global optimization for preserving the curve length is developed.

Fig. 2 shows design examples with our system in which places of different heights that can be connected on a FPC, places of different connecting directions, and places at orthogonal orientation respectively. The user modifies or adds the control points to edit the curve and every time the control points are changed the curve’s length is adjusted.

Conclusions
A design system is developed for 3D bending shapes of FPCs in electronics devices. The 3D bending shape of a flat FPC is generated as a rectifying developable surface using a control curve and the profile shape of the FPC. To facilitate the design process, two kinds of functionalities are implemented; boundary condition setting and curve length preservation. Some simple
examples are demonstrated using the proposed system. It is shown that the surface generation can be made at interactive rates with sufficiently accurate length preservation.

As future work, we have to extend the boundary conditions for dealing with general ruling directions. We also need to consider FPCs with more complex profile shapes, particularly those with branching structures. In such cases, the recognition of the skeleton structure of the FPC is considered the most difficult problem. It is also important to develop a method for generating special folding patterns which are often used in electronics devices.

![Image](image1.png)

**Fig. 1:** Design of 3D bending shape of FPC using rectifying developable surface method [2].

![Image](image2.png)

**Fig. 2:** Examples of FPC surface generation using our prototype system. (a) FPC connecting two places of different heights. (b) FPC folded by 90 degree. (c) FPC of a looped path.

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**References**
Extended Abstract 88

Title
GPU Parallel Computation of Bio-Material Damage

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Keywords
GPU, Parallel Computation, Bio-Material Damage, Computer Aided Design

Introduction
GPU is an emerging graphics processing unit that can be used to accelerate general-purpose scientific and engineering applications. Digital diagnosis of material damage is an effective way to explore the damage and failure mechanism of various bio-materials, and is also a useful way to monitor the damage status or state of bioengineering components or structures. Unfortunately, digital quantification of material damage is a complex process that involves high computational costs due to the irregular microstructures and defects of material domains. Digital radiography and computed tomography of T-ray [1], gamma ray [2], neutron [3], synchrotron [3], ion beam [4], and X-ray [5-10, 10-13] generate a huge number of two-dimensional/three-dimensional (2D/3D) digital images, in which immense amounts of material defect data are embedded. In this paper, parallel computation of bio-material damage is studied with CUDA (Compute Unified Device Architecture) programming. In particular, we investigate an effective computational method for solving linear equations of finite element analysis of material damage on the basis of volume data from a computed tomography system.

Main Idea
Kernels are the programs that run on the GPU. Kernels are meant to do calculations on the GPU. The user should only store active data on the GPU. In this section we discuss the different kernels used for the LU factorization, their uses and their evolutions. The first set of kernels is used as utility kernels. These kernels prepare the data for the calculations and copying to and from the host. These consist of init kernels which are used to initialize the matrixes, merge the matrixes, and initialize the profile.

Two kernels were used to initialize the profile array. The main inputs are a matrix, the dimension of the matrix, and an array to maintain the profile. The first is used with any matrix. The second is for matrixes with pitched memory, so the pitch is an extra parameter. In this kernel each thread in each block is used to find the pitch for a unique row. This initialization is on the order of $n$ since it is run in parallel where if it were run in serial it would be on the order of $n^2$.

Two kernels were used to initialize the L matrix. Both the initialization matrixes are set the L matrix to the identity matrix. The difference in the two is that the first one is created for use with any matrix and the second one was created for use with a matrix that is using pitched memory. There are three merge kernels. The first two merge the L matrix with the U matrix. The inputs are the two matrixes and the dimension. The second was created for pitched memory and thus needs the pitch for the two matrixes. The result is that the second matrix has LU overlapped where the diagonal and above is U and below the main diagonal is L. The third merge kernel merges the matrixes LU into DL$^T$. This is done by keeping the main diagonal from U and the upper elements are from L$^T$.

Digital Quantification of Material Damage. In this study, a high-energy and high-resolution micro-focus X-ray computed tomography system (XCT) is used to measure all the voids and cracks in material test specimens (Figure 1(A)). It was made by Phoenix X-ray Company in 2008. The maximum power and voltage of X-ray tube are 320 W and 225 KeV, respectively. The detail detectability of this instrument can be down to ten micrometers. Test material specimens are manufactured according to the standard (Section 03 – Metals Test Methods and Analytical Procedures) of the American Society for Testing and Materials (ASTM). The loading and displacement of the test specimens are measured by one of two material testing machines (MTS 810), while the surface displacement and strain of the specimens are determined by a high-resolution ARAMIS optical measurement system for three-dimensional deformation. The deformation measurement range of the ARAMIS system is between 0.01% and several 100%. NVIDIA Tesla GPUs were used to conduct the digital diagnosis. Figure 1(B) demonstrates a multiscale approach to the digital quantification of material damage.
Conclusions
In this paper, a parallel computation method is developed for the digital diagnosis of bio-1-material damage. CUDA programming language was used to conduct multi-block and multi-thread computations. Numerical results indicate that significant saving can be achieved by the GPU parallel computing in the context of material damage analysis.

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References
Extended Abstract 89

Title
Quality Improvement of Deformed Mesh Models for FEA by Density and Geometry-recovering Phased ODT Smoothing

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Keywords
Quality Improvement, Tetrahedral Mesh Model, Mesh Deformation, Optimal Delaunay Triangulation Smoothing

Introduction
In current product shape design, to find optimal shape parameters, the solid modification, meshing, and FEA are repeated until a desired product shape is obtained. For reducing the frequency of meshing processes which are unstable and time-consuming, dimension-driven mesh deformation methods have been proposed [2]. However, the deformed mesh models often include many distorted elements, and lose the original mesh properties (mesh density and shape approximation accuracy). Therefore, for accurate and efficient FEA, a new method which improves element shapes and recovers original mesh properties in the deformed mesh model is required.

Many quality improvement methods have been proposed. Especially, Optimal Delaunay Triangulation (ODT) smoothing [1] is effective for mesh quality improvement. However it cannot recover the original mesh properties, because it improves element shapes only by moving vertices and flipping operations. Moreover, it cannot improve element shapes on the boundary. To solve these problems, we develop a new quality improvement method for the deformed mesh models. We assume that inputs of our method are tetrahedral mesh models which consist of planar and cylindrical surfaces.

Main Idea
Overview of our method
Our method is based on ODT smoothing [1] with edge split and edge collapse, and it has four features. First, to improve all element shapes, our method progressively improves element shapes from the boundary to the inside (sharp edges, surface triangles, and tetrahedra in that order) using ODT smoothing (Fig. 1). Second, to recover the mesh density of the original mesh model in the deformed mesh model, the target mesh density field represented by a regular grid is generated, and edge split and edge collapse according to the field are performed during ODT smoothing. Third, to recover the shape approximation accuracy of the original mesh model, acceptable geometric error is calculated from the original mesh model, and edge split is applied during ODT smoothing depending on the error. Finally, degenerated and inverted tetrahedra are removed by our new method based on the combination of edge split and edge collapse.

Target Mesh Density Field Generation. For recovering the mesh density of original mesh model in the deformed mesh model, our method generates a target mesh density field. At first, mesh density at each vertex of the original mesh model is calculated as the average of reciprocals of incident edge lengths. Secondly, the mesh model is deformed using mesh deformation method. Then, a regular grid including the deformed mesh model is generated. Next, mesh density of each grid point is estimated by barycentric interpolation of the mesh density of the deformed mesh model. Finally, mesh density of each grid cell is calculated by taking average of its corner grid points.

Geometry Extraction. Sharp edges, surface regions, and their surface parameters are extracted as follows. First, the segmentation by thresholding of dihedral angles and region-growing is performed, and surface regions (segments) and sharp edges are

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
Page 195 of 226
extracted. Secondly, by surface fitting, each surface region is classified into either a planar or cylindrical region, and its surface parameters are extracted. Finally, each sharp edge is classified into either a straight line segment, a circular arc, or a circle according to types of neighboring surface regions. These processes are applied to both the original mesh model and the deformed mesh model. In each cylindrical surface region of the original mesh model, acceptable geometric error is calculated as the maximum distance between the fitted cylinder and mesh edges in the region.

**Phased ODT Smoothing with Edge Split and Edge Collapse.** In ODT smoothing, flipping and vertex repositioning are iteratively applied to given mesh models. The flipping is topology optimization which generates Delaunay triangulation from given triangulation. The vertex repositioning is geometry optimization which moves each inner vertex to the weighted average of circumcenters of its neighboring elements. ODT smoothing cannot improve element shapes on the boundary. To improve all element shapes, our quality improvement method consists of three phases; sharp edges improvement, surface triangles improvement, and tetrahedra improvement.

In the sharp edges improvement, for straight line segments, the vertices are moved to the average of midpoints of its neighboring edges. On the other hand, for the circles or circular arcs, the vertex repositioning is performed on 1D parameter space based on central angle. In this phase, flipping is not applied. In the surface triangles improvement, for planar regions, original 2D ODT smoothing is performed. On the other hand, for cylindrical regions, the vertex repositioning is performed on 2D parameter space given by the surface development. In our method, the edge flipping is realized by the combination of edge split and edge collapse for topological consistency preservation of inner tetrahedra. In the tetrahedra improvement, original 3D ODT smoothing is used.

After the vertex repositioning in each ODT smoothing, edge split and edge collapse are applied to control mesh density and shape approximation accuracy. Edge split (or collapse) is applied to the edges in the region which has higher (or lower) density than the one from the target mesh density field. For shape approximation accuracy, edge split is applied to the edges which have larger approximation error than the acceptable geometric error, and the new vertex generated by the edge split is moved to the fitted surface.

**Degenerated and Inverted Tetrahedra Removal.** In each phase, degenerated tetrahedra, such as sliver or cap, are removed by the two step local topological operations. First, degenerated tetrahedra are divided by edge split. Secondly, edge collapse is applied the newly generated short edge. As a result, the degenerated tetrahedra become triangles. And inverted tetrahedra are removed by the half edge collapse.

**Conclusions**

In some experiments, our method could greatly improve most mesh qualities. Fig. 2 shows the original mesh model (a), the deformed mesh model (b), the improved mesh model by original ODT smoothing (c) and by our method (d), and each cross section view. Stretch is an element shape quality measure which is 1 for regular tetrahedron and 0 for the degenerated one. The average stretches of each mesh model are (a) 0.53, (b) 0.45, (c) 0.52, and (d) 0.70. The minimum stretches of each mesh model are (a) 0.08, (b) -0.22, (c) -0.28, and (d) 0.19. The average mesh density errors are (b) 0.31, (c) 0.29 and (d) 0.17, and the average geometric errors are (a) 0.10, (b) 0.12, (c) 0.12, and (d) 0.07.

![Fig. 2: Result of improvement of the deformed mesh model.](image)

**References**


Extended Abstract 91

Title
High-Quality shape fitting for aesthetic modeling based on Class A condition

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Keywords
High-quality shape modeling, aesthetic property, reverse engineering, surface fitting, Class A

Introduction
The significance of aesthetic aspects in product design has grown rapidly. To survive severe global competition, designers have been urged to generate original and appealing shapes wherever possible. However, the uniqueness of shapes is not necessarily the only interest in industrial design; the quality of shapes also plays an important role in the exterior design of products. Therefore, uniqueness should be harmonized with shape quality even in the early stage of design because it becomes increasingly difficult to modify the shape in later design stages. However, support tools for designers to achieve not only unique but also high-quality shapes have not been sufficiently available. Thus, in this paper, we propose a novel design framework based on the “Class A” concept. Moreover, an application system for reverse engineering situations was constructed and its effectiveness was demonstrated.

There have been some related studies in which the generation of aesthetic shapes has been the main target. Higashi et al. [1] proposed a method of generating smooth surfaces by controlling the variation of curvature. Then, Mineur et al. [2] presented an important definition of a typical curve, which was defined as a form of a planar Bézier curve whose curvature is monotonic. Farin [3] proposed the concept of Class A Bézier curves. The term “Class A surface” had previously meant a high-quality surface that is required for the outer parts of automobiles. Farin redefined this term as a general form for typical curves and presented mathematical conditions for a 3D Bézier curve to be a Class A curve. Oya et al. [4] presented a design method based on this Class A concept. They constructed a design system in which the Class A matrix was decomposed by singular value decomposition (SVD) and each decomposition parameter was used as a design parameter in the system input. Using this system, shapes can be created intuitively with guaranteed high quality.

In this study, we focus on reverse engineering, which is nowadays a very important process in product design. In a typical reverse engineering scheme, a 3D scanning instrument acquires point data, then appropriate data processing is conducted on CAD software. This process is not a creative activity and considerable time is usually required to recover the original shape. Furthermore, the recovered shape is not necessarily the desired shape even if the noise is completely removed because the modeler creates the model, which is usually a clay mockup, rather than the designers. An interpretation gap generally exists between the shape created by a modeler and the shape intended by a designer. Therefore, extra modification is required to obtain the genuinely desired shape.

The proposed method is based on fitting using a subdivision surface technique, the Class A definition, and a genetic algorithm (GA). First, we prepare point clouds to be interpolated. Then, the fitting scheme based on subdivision surface is performed so that its limit surface passes through the points smoothly. In this phase, we adopt the Catmull-Clark subdivision scheme because of its rectangular domain, which is preferable in CAD representation, in which quadrilateral surface patches are used. The final output of fitting using subdivision surface is a set of control points of parametric surfaces such as B-spline and Bézier patches. However, unfortunately, the obtained smooth surface is not necessarily the desired one for the reason explained above. In other words, the recovered surface resembles very closely the ideal shape. A new algorithm was constructed to deal with this problem. The Class A definition is applied in the form of conditions on the Bézier control points so that the Bézier curve or surface is monotonic in its curvature. Monotonicity in curvature is a very important concept in this study because it is preferable in industrial design and we desire it in the target shape. It is assumed that designers desire shapes whose curvature is monotonic as an essential part of their designs. Thus, in the next process in our system, we attempt to obtain appropriate Class A matrices by using a genetic algorithm. Here, a Class A matrix is a matrix that determines each control point and satisfies the condition for monotonicity in curvature. The genetic algorithm is applied to modify the components of matrices so that the entire control point network becomes that of a shape whose curvature is monotonic. To avoid excessive modification, a constraint is imposed on the recovered shape so that it remains similar to the scanned shape. This is achieved by evaluating the distance between the original shape and the ideal shape. A designer can choose the preferred shape from various candidates; therefore, the intended high-quality shapes are always obtained without the inefficient manipulation of control points. A schematic illustration of the proposed algorithm is shown in Fig.1.

Results
We tested the proposed method on single surface patch, as shown in Fig. 2. Beginning with point data shown in Fig. 2 (a), we conducted the process of the fitting technique based on the Catmull-Clark subdivision, which resulted in control points shown in Fig. 2 (b).
The surface recovered from these control points will pass through the input data; however, it is not necessarily an intended shape. It is assumed that a designer wishes to have a high quality surface but the points include noises and interpretation gap. Then we performed an optimization scheme to modify the location of control points to satisfy the Class A condition. The results are shown in Fig. 2 (c) and (d). We deemed that the final surface is sufficiently close to the measured points and satisfies a demand for high quality.

Conclusions
In this study, we present a novel reverse engineering technique that enables designers to obtain intended high quality shapes by the Class A condition and optimization scheme. The system produces high quality shapes that are very close to the physical model. And designers can select the most preferable shape from the candidate that the system generates; therefore, truly desired shape can be obtained efficiently.

Fig. 1: Schematic of the proposed Class A fitting process. Fig. 2 Example of the proposed method.

References
Extended Abstract 92

Title
Study of a point cloud segmentation with part type recognition for tolerance inspection of plastic components via Reverse Engineering

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Keyword
Reverse Engineering, Computer Aided Tolerance Inspection, Segmentation, Plastic Injection Moulding

Introduction
Automatic inspection of tolerance via Reverse Engineering techniques is appreciated to reduce time to market and it is growing thanks to the improvements achieved in the field of non-contact measurement systems. Its workflow [1,3] can be regarded as a general measurement protocol similar to that ones applied to a Coordinate Measuring Machine (CMM) but enriched with CAD capabilities, like data management and automatic extraction of tolerance specification and solid model reference (Fig. 1(a)).

![Diagram](image.png)

Fig. 1: Computer Aided Inspection workflow: (a) based on CMM measurement protocol; (b) based on part type recognition.

Bottlenecks of such implementation are the registration of the point cloud with the CAD model (that may ask for expensive fixtures), the accuracy of the multiple view recomposition and the efficiency of the segmentation algorithms. From the industrial point of view, they represent time consuming steps since they require manual interactions between CAD model and Reverse Engineering software [5]. In case of inspections on a large number of electromechanical plastic specimens, as it happens during injection moulding die set-up, these interactions must be avoided and generally, no specific fixtures are used except a reference table. So, point cloud and CAD model registration becomes less relevant. Moreover the results of the inspection often require the report of many dimensional tolerances, better described as standard 2D technical drawing or datasheet instead of a deviation distribution on a solid model. These practical needs justify the research of ad
hoc procedures able to by-pass the registration phase allowing a virtual inspection that is stand alone from the CAD model, except for the tolerance specification extraction (fig. 1(b)).

Main Idea
This paper presents a point cloud segmentation based on a spatial multiresolution discretisation derived from hierarchical space partitioning [4]. A voxel structure encompasses and subdivides the point cloud. Then, through a suitable surface partitioning, it is linked to component volumes by means of the morphological components of the binary image that is derived from voxel attributes (‘true state’ if points are included in a specific cluster or ‘false state’ if they are not). The volume recognition is performed by means of a part type segmentation according to a problem of feature recognition, [2]. Doing so, the proposed approach aims to simplify Computer Aided Tolerance Inspection of electromechanical components avoiding cloud-CAD model registration. These components typically have dimensional tolerance > 0.05 mm, in the range [25, 150] mm, and can be easily acquired by commercial laser scanners for quality inspection.

Through an ad hoc definition of the adjacency list of the filled voxels, a rough estimation of the global part shape can be achieved as follows. Analysing the planarity of the points inside every voxel a surface partition is made. Then each plane found through the cluster analysis is considered a potential start or end plane for a protruded detail of the component. Reading as a binary image the 2D voxel matrix associated to a generic plane of a cluster and comparing it to the binary image of the next sections (that are derived in the same way) a protruded volume exists if the morphological components of these images are comparable.

The proposed approach has been tested on a din-rail clip of a breaker, acquired by a Nikon LC15DX laser scanner placed on a CMM controller system (3Coord Hera 12.9.7). Fig. 2 summarises the results in terms of: (a) filled voxels surrounding the cloud; (b) localization of non planar surfaces (blue points); (c) clusters of planar regions.

![Fig. 2: Din-rail clip: (a) 3D structure of ‘true state’ voxels; (b) voxel detection with small radii or non planar region, blue points; (c) clusters found for planes perpendicular to the reference axes - blue x axis; magenta y axis; green z axis.](image)

After this the part type recognition is performed starting from the clusters of planes. Fig. 3 gives an example of normal protusion recognition along the y axis. Fig. 3(a) shows the binary images of the voxel sections referred to the two widest planes. In the lower part the results of the boundary tracing is shown in terms of labeled areas. Fig. 3(b) shows the associated volumes found through a comparison of the bounding box of each area of the section with that of the neighbouring ones, according to: (i) centroid position, (ii) area of the filled region and (iii) number of closed area included in the bounding box.

![Fig. 3: Part type recognition: (a) binarisation and boundary tracing of two plane section normal to the y axis; (b) volume recognition](image)
Conclusion

Thanks to the component shown in Fig. 2(b), evidences are given about the feasibility of the proposed approach. Some considerations can also be pointed out about the assumptions necessary to set up the proposed approach. They concern with the density of the voxel discretisation and the two thresholds necessary for the surface partition. The total number of voxels must be set as a function of the smallest significant length of the component. Doing so it can be demonstrated that the proposed approach is able to investigate box-shaped components also with small thickness. These kind of shapes can be assumed as the most relevant for electromechanical components made by injection moulding. The two thresholds necessary to perform the surface partition can be easily set to reach the automation of the procedure, as discussed in the paper. Finally some consideration about the computational efforts. At the moment they are mainly due to the voxel creation and partitioning, requiring about $10^2$ s/points. Speed improvements have been planned through parallel computing.

References


Extended Abstract 93

Title
Weaving a four-dimensional mesh model from a series of three-dimensional voxel models

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Keywords
Four-dimensional model, tetrahedron mesh, voxel model, marching hyper-cubes

Introduction
Four-dimensional data representation and analysis are now required in various fields such as robotics[3], manufacturing[4], building construction[5], medical science[2] and so on. The ways of four-dimensional data descriptions and operations deeply depend on the fields of applications, and the most implementations of four-dimensional space remain at the set of three-dimensional models indexed with time. The approach of four-dimensional geometric modeling enables us to represent a dynamic object with motion and deformation as a static shape in space-time. The authors have been studying four-dimensional geometric modeling from 2007 and developing a four-dimensional mesh modeling system (4-D Mesh Modeler). As a part of 4-D Mesh Modeler, a subsystem for model generation has been implemented as shown in Fig. 1. The subsystem, named 4-D Mesh Weaver, generates a four-dimensional mesh model from a series of three-dimensional voxel models. The data processing algorithm and geometric data structures for four-dimensional tetrahedron meshes are explained in this paper.

Main idea
Four-dimensional mesh generation in 4D Mesh Weaver is based on a Marching cube algorithm extended for four-dimensional data by Bhaniramka [1]. IN-OUT flag values of a hyper-cube’s vertexes are encoded to a 16 bits vector and used as an input value for a tetrahedron generation table. Because the numbers of both vertexes and tetrahedrons generated as four-dimensional elements are much larger than those for three dimensional geometries, the mesh generation algorithm used in 4-D Mesh Weaver has been improved by preprocessing the tetrahedron generation table, eliminating vertex-merge step and compact representation of four-dimensional elements.
The result of 4-D Mesh Weaver is a four-dimensional mesh model which boundary is covered with tetrahedrons in four-dimensional space. Tetrahedrons, which are boundary mesh elements, are locally grouped in an AABB (axis-aligned bounding box) tree, and adjacent tetrahedrons are linked each other as neighbor element. By cutting a four-dimensional model with a hyper-plane, a three-dimensional model can be extracted as cross section in four-dimensional space as shown in Fig. 2.

![Fig. 2: Hyperplane cutting views of 4-D mesh model by 4-D Mesh Viewer.](image)

**Conclusions**

Four-dimensional geometric modeling is not a new idea itself, but it has been considered as an impractical idea due to its larger data size, longer processing time, complex data structure, and hard-to-understand operations. The increasing capability of computer hardware and software is gradually resolving these problems so as to make the idea of 4-D geometric modeling practical.

This paper dealt with only a small part in the 4-D geometric modeling framework. Input and output data were limited to a series of 3-D voxel models and a 4-D mesh model respectively. This combination is the first step and the authors have a plan to examine various combinations of spatio-temporal input data models and 4-D modeling methods. For example, the authors are now developing a 4-D shape representation and operation method based on implicit function. The authors expect that 4-D geometric modeling can contribute to find new approaches to spatio-temporal problems in various fields such as design, manufacturing, robotics, computer vision, medicine, geoscience and so on.

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Extended Abstract 94

Title
Knowledge management for the selection of 3D digitizing systems in relation with application requirements

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Keywords
3D digitizing system, knowledge management, database, quality, ability criteria, reverse engineering

Introduction
During the last years a large number of 3D measurement system have emerged. These systems used a wide range of technology and have various characteristics. They are used for varied applications such as reverse engineering, part inspection, direct machining, digital art... The common feature of these systems is their ability to collect a large amount of data in a very short time. This last point is often an important argument for industrial applications. However, the quality of the resulting cloud of points depends on various factors. The large amount of data is not a quality guarantee of resulting cloud of points whereas data quality plays a decisive role for success of the application [1-3]. The issue that arises is how to choose a measurement system that guarantees the quality required for a given application. This issue can be solved if data quality becomes the central point of the selection process of the digitizing system. In this way it is necessary to define quality criteria related to the application, to the point cloud, and quality criteria for the assessment of 3D measurement systems. The implementation of these criteria will result in the generation of a large amount of information to deal with.

The aim of this paper is to define a Digitizing System Database (DSD) to organize, connect and analyse those knowledge in order to select the best 3D digitizing system regarding a given application. The knowledge management is success thanks to a database that allows to link ability, quality criteria and system performance. A reverse engineering application will illustrate the introduced concept.

Main sections
In the literature, knowledge management is often approached as an issue of information modelling. The final goal is to build models and Meta models, allowing the capitalization and the use of knowledge in other applications. In our case, we are not looking to build a model of treated knowledge but to organize and link a large amount of information coming from various independent sources as sensors, displacement device, geometric constraints, dimensional constraints… There is a peculiarity in the process of digitizing systems selection; the necessary information are not intrinsically linked. It is therefore necessary to provide a tool to link and navigate through the flow of information processed to achieve the selection of a measurement system for a given application. In this way, we use ability and quality criteria and we propose a cost function based on digitizing complexity concept. Digitizing system selection (Fig.1) can be divided in 3 activities: application requirements analyses (in term of geometric, dimensional constraints...) and identification of surfaces to digitize; Identification of admissible systems regarding application requirements and identification of the best system by minimizing a cost function.
An analysis of the application requirements and the study of the part to digitize (in term of geometry and dimension) allow identifying the minimum quality necessary for the digitizing of each surface. The selection of the system is done thanks to the Digitizing System Database (DSD) that is divided into two databases: the intrinsic database and the qualified database. The admissible systems are identified according system ability criteria and data quality criteria in accordance with requirement resulting from previous step. We consider the digitizing system as a combination of a sensor and a displacement device. Ability is then assessed through the accessibility of the systems regarding part geometry, scale of measurement, workpiece rigidity, surface colour, resolution, field of view... Those information are coming from systems manufacturer and are stored in the intrinsic database (ID) (Tab. 1(a)). According to requirements, each sensor and displacement device is set by various ability indices (0 or 1). An ability selection algorithm allows us to browse the ID identifying admissible systems. Considering two quality criteria well addressed in the literature, trueness and noise [3-5], the number of admissible systems is reduce.

In order to select the best system, a cost function $c(k)$, to be minimized is introduced. The function is a combination of four cost indices (CI): digitizing speed CI for completeness ($Ds$); digitizing speed CI for density ($Dsd$); FOV depth CI for noise ($Fdn$) and FOV depth CI for trueness ($Fdt$). Each CI is a ratio between the system performance and the higher CI value. The cost function is given by equation (1):

$$c(k) = \sum_{i=\{Ds,Dsd,Fdn,Fdt\}} \rho_i \cdot c(i,k)$$

Where $\rho_i$ is weight index of $c_i$ and $\Sigma \rho=1$. The computation of $c(k)$ is perform thanks to the qualified system data which are obtained by a 3D digitizing system assessment protocol called QualiPso [9], and stored into the qualified database (Tab. 1(b)).

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Table 1(a). Intrinsic database, (b). Qualified database.

Conclusion

By the management of a large set of knowledge, the best digitizing system is selected thanks to the application requirements. Starting from the analysis of input information (application, CAD model, piece work part...) surfaces to be digitized and associated requirement are defined. Admissible digitizing systems are selected allowing the surface acquisition according to ability and quality criteria. The best system is obtained by optimizing a cost function built from performance acquisition criteria. Ability, quality and performance information are managed thanks to a Digitizing System Database (DSD), which consists of two databases, the intrinsic database and the qualified database.

References


Extended Abstract 95

Title
In-Situ Measurement and Distributed Computing for Adjustable CNC Machining

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Keywords
Geometrically Adjustable Machining, Computer Numerical Control, Laser Scanning, Reverse Engineering, MTConnect

Introduction
Computer Numerical Control (CNC) machining is the established standard for producing the final shape of cast or forged parts, heat treated injection mold cores and cavities, etc. The associated surfaces are complex, and require sophisticated geometric CAD/CAM tool path planning and 3- to 5-axis machine tools to successfully produce. The CAD representation is assumed to represent the nominal part shape. Because of a lack of computational and in-situ measurement resources, there is little support for at machine registration and other adjustments to correct for actual surface geometry.

This paper describes progress towards provision of touch trigger probe and laser digitizer (or scanner) measurement resources at the machine tool, with supporting computational resources accessed via Ethernet. The emerging MTConnect standard provides executive level monitoring. Illustrative examples include fixture registration using datum spheres, aeroengine assembly weld machining, and associated data fitting and tool path adjustment. The goal is to develop an environment with a higher level of intelligence and decision making ability for machining under variable geometry conditions.

Architecture
The proposed architecture is shown in Fig. 1(a). Measurement devices such as a laser scanner and touch trigger probe are installed at the machine tool. Where possible, such as with a touch trigger probe (Fig. 1(b)), data integration is first made with the motion control. The advanced geometry mathematics is accomplished by passing the raw (DPRNT) measurement data through an Ethernet capable Universal Machine Interface (UMI) to a (possibly remote) Mathematics Engine computer. Laser scanner (Fig. 1(c)) integration is provided mechanically, with the high point cloud data volume transmitted over Ethernet to the remote computer. The Mathematics Engine implements feature data fitting such as least squares planes, spheres, cylinders, etc. Registration between nominal CAD and actual data is also attempted to ensure that sufficient material is available to continue with machining, that the fixture is not distorted, etc. Unsuccessful registrations are reported immediately, avoiding valueless machining operations. For successful registrations, the nominal CNC tool paths are customized by appropriate geometric transformations, feed rate adjustments, etc., and transmitted back to the machine tool motion control for execution. Monitoring, either by the operator at the machine tool, or at an executive level, is provided using MTConnect [1].

Example Results
A partial cylinder was attached to a planar fixture and three datum spheres (Fig. 2(a). In the reference pose 0, the datum spheres were measured using a touch trigger probe, and the centers located using an orthogonal least squares fit. The entire right side of the surface was machined. The setup was then re-clamped in slightly modified poses 1-4. In each pose the datum spheres were re-measured and compared to the reference pose. If the sphere to sphere distances were significantly different, the fixture plane was measured for flatness. If not flat, excessive clamping force is indicated and the operator is prompted to correct. After any necessary adjustment, the CNC tool paths are transformed using the computed reference to pose transformation. A photo of the result, with laser scanner measurement data, is shown in Fig. 2(b), (c).

Separately, a stub aeroengine blade was added to the cylinder geometry, and welded around the fillet. Slight perturbations in the cylinder to blade position were intentionally introduced. The actual geometry was laser scanned, registered to nominal, and the tool paths adjusted accordingly. A representative photograph and measurement data is shown in Fig. 3. These results show the promise of the system, and continuing work will include extension to a 5-axis machine tool and further laser scanner integration with the CNC machine tool.
Acknowledgements
This work was financially supported by the NSERC Canadian Network for Research and Innovation in Machining (CANRIMT).

References

Fig. 1: (a) measurement/computing system architecture; (b) touch trigger probe; (c) laser scanner (shown on CMM)

Fig. 2: (a) datum sphere fixture and part setup; (b) pmachined part photo; (c) measurement results

Fig. 3: (a) machined cylinder/blade; (b) measurement results
### Extended Abstract 96

**Title:**
A review on 3D Object Retrieval methodologies using a part-based representation

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**Keywords**
3D object retrieval, 3D mesh segmentation, part-based representation

**Introduction**
The rapid growth in the field of 3D capture technologies has led to the continuous expansion and enlargement of 3D object databases. Therefore, the construction of retrieval algorithms that enable efficient and effective 3D object retrieval from either public or proprietary 3D databases is becoming a necessity. 3D object retrieval is the process which retrieves 3D objects from a database in a ranked order so that the higher the ranking of an object the better the match to a 3D object query, using a measure of similarity. Various methods exist in the literature, which use a global descriptor to represent the object. However, humans tend to recognize objects by analyzing the semantics of their parts. This leads to the hypothesis that two objects are similar, if they consist of similar parts.

In this paper, we strive towards presenting a comprehensive overview of methodologies on 3D Object Retrieval using a part-based representation detailing the key aspects, and discussing advantages and pitfalls of each methodology.

**How methods work**
A typical operational pipeline for 3D object retrieval methodologies based on a part-based representation comprises the steps that are described in the sequel. First, a 3D mesh segmentation algorithm is applied to all the objects of the database. Adjacency of the parts that are generated is taken into account to construct a graph representation of the object. Each part is represented as a node while edges express the relation of adjacent parts. The next step is feature extraction applied on each extracted part. Each node of the graph is associated with a feature vector with geometric attributes of the corresponding segment. Furthermore, each edge of the graph can be attributed to pairwise features, i.e. features that correspond to the boundary of two segments or features that involve two adjacent regions in general. The final step is related to graph matching. The problem can be summarized as follows: given two attributed graphs the goal is to find the minimum distance that represents the dissimilarity of the two objects. Thus, a correspondence has to be found between nodes of two distinct graphs.

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<td>C, Conv</td>
<td>-</td>
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<td>global</td>
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<td>global</td>
<td>Euclidean distance</td>
<td>Tree search</td>
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Tab. 1: Methods overview.

The following abbreviations are used in Tab. 1: IG: integral geodesic function, SDF: shape diameter function, A: area, V: volume, C: curvature, Conv: convexity, CF: discrete conformal factor, EE: eccentricity values of ellipsoid representation, SH:
spherical harmonic descriptor, \textbf{Dbary}: distance from mesh barycenter, \textbf{DS}: distance between segment centers, \textbf{AS}: angles between segments’ principal axes, \textbf{GD}: geodesic distance between boundaries.

Acknowledgements
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References
Extended Abstract 97

Title
A Rendering Method of Laser Scanned Point Clouds of Large Scale Environments by Adaptive Graphic Primitive Selection

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Keywords
Laser Scanning, Point Clouds, Rendering, Graphic Primitives, Mesh, Splat, Level-of-Detail

Introduction
Long-range laser scanners allow us to easily acquire the point clouds of large scale environments such as manufacturing plants, roads, buildings, urban areas and cities. Scanned point clouds are widely used in many applications of several areas, and rendering of the scanned point clouds is one of the most basic operations in them. However, it is often difficult to recognize the scanned environments or objects in the environments by seeing the point rendering results because of the gaps between the points. Splatting [1] and surface generation techniques can be used to improve the quality of rendering results of the point clouds data. However, they do not work well for the point clouds of large scale environments because of the extremely non-uniform point densities and spatial distributions, and the existence of various kinds of objects with different scales and shape complexities.

In this paper, we propose a new rendering method of the laser scanned point clouds of large scale environments for supporting human's easy recognition of the scanned environments. Our method is based on the adaptive selection of the graphic primitives, octree-based hierarchical points representation, and view dependent LOD in order to realize effective and efficient rendering of the laser scanned point clouds.

Main Idea
Fig.1 shows the overview of our research. In order to realize effective rendering of the laser scanned scenes, simple rendering model is created by using principal component analysis, region growing and adaptive graphic primitives selection (Fig.1, A1-2). The model consists of three types of primitives; straight line segments, rectangular splats, and triangular meshes. The line segments are used for representing thin objects such as power lines. Planar surfaces such as road and wall of buildings are represented by the rectangular splats. Other complex 3D objects such as trees are represented by the triangular meshes. The created model is used for rendering the close views of the scanned environments. As a results, the gaps between the points are filled, and objects are appropriately represented in the rendering results.

Efficient rendering is also realized using LOD techniques. In our rendering, original or down sampled points are used to render the distant views of the scanned environments. Therefore, the point hierarchy is created by using the octree structure and random point sampling (Fig.1, A3). For the LOD in the close views, simplified versions of the rendering model are also created by using simplification method for the primitives (Fig.1, A2). In the rendering phase, view-dependent LOD

Fig.1 Proposed rendering method of point clouds data of large scale environments

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10
according to the distance from the viewpoint is performed using point hierarchy and rendering models related to the octree (Fig.1, A4).

**Point classification and segmentation (Fig1. A1).** First, at each point in the point clouds, principal component analysis (PCA) is done using its neighbors for analyzing the local point distributions [2]. Using the results of PCA, each point is classified into three types; 1D, 2D, and 3D point, where n-D point means that the distribution of its neighbors is n-D (1D: linear, 2D: planar, 3D: volumetric). In order to realize efficient PCA of the point clouds with non-uniform point densities and distributions, neighbors search radii in PCA are adaptively and automatically determined according to the local point density evaluation. After the point classification, region growing is applied to the classified point clouds to correctly classify the points on the objects boundary, which are not correctly classified by PCA. Finally, points with same classification results are gathered by Euclidean distance-based clustering or region growing, and segments of the objects are created.

**Rendering model creation by adaptive graphic primitive selection (Fig1. A2).** For 1D point segments such as power lines, sequences of the straight line segments are generated as the graphic primitive in the close views. The sequences are created by connecting two neighboring points along the principal direction of largest eigenvalue obtained by PCA. For 3D point segments, triangular meshes are generated. For each 2D point, a rectangular splat is created. The normal of the splat is the principal direction of smallest eigenvalue, and its sides parallel to the other two principal directions. The size of splat is determined according to the distance between the closest points. For LOD rendering, the sequences of line segments are simplified by combining two neighboring points, and the mesh is simplified by traditional mesh simplification algorithm (QEM is used in our method). Neighboring similar splats are combined into large one for LOD rendering.

**Point hierarchy creation and view dependent LOD (Fig1. A3-A4).** For the distant view of the scanned environments, a hierarchy of the point clouds is created by adaptive space subdivision using the octree, and quantization in each octree cell [3]. Leaf nodes of the octree include original points, and the nodes are related to the segments obtained by the segmentation process. View dependent LOD is done depending on the distances between the octree cells and the viewpoint. In the rendering process, down-sampled points, original points, simplified rendering models and complete rendering models are adaptively rendered according to the distance from the viewpoint.

**Conclusions**

Fig.2 shows two examples of rendering results of simple point rendering (left) and our method (right) for the point clouds of large scale environments. Gaps between the points were filled, and easy understanding of the scanned environment was realized. Compared with the traditional splatting and mesh generation methods, it was confirmed that our rendering model based on point classification provides more natural and accurate rendering results.

In this paper, a new rendering method of the point clouds for supporting easier understanding of the laser scanned environments was proposed. Our method is based on the rendering model generation by adaptive graphic primitive selection, point hierarchy generation by octree structure, and view dependent LOD.

![Fig.2 Results of our rendering method for point clouds from mobile laser scanning and terrestrial laser scanning (left figures in (a)(b) are the point rendering results, and right figures in (a)(b) are the rendering results of our method.)](image)

**References**


Extended Abstract 98

Title
REFM: A Reverse Engineering For Manufacturing approach

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Keywords
Reverse Engineering, manufacturing, knowledge extraction, process planning, Design For Manufacturing

Introduction
Industrial companies are confronted to reverse engineering on mechanical components. They have to define a new process planning from 3D information (points cloud). A first approach is to reconstruct a CAD model of the part to be reversed which then is reintroduced in the conventional product lifecycle. Another approach is to directly identify manufacturing operations and define a new process planning from 3D information. In our research, we propose an approach called Reverse Engineering For Manufacturing (REFM) which allows to directly obtain a CAPP (Computer Aided Process Planning) model from 3D and knowledge information. The system management is based on Design For Manufacturing (DFM) approach and enables to manage manufacturing information (such as the number of fixtures, the kind of milling operations, etc.). In addition, the future REFM system will have to propose alternatives for CAPP models. REFM aims to integrate databases that contain all the necessary information for the construction of the CAPP model. In this context, the system of Ashy et al. [1] CE54.5 is adapted.

Main idea
RE methodologies are able to duplicate complex parts; however they can capture a very low level semantics. Or, a CAD model is not only a geometrical model. Additionally in design, functional aspects are often attached to geometric shapes. So today, it is necessary to integrate in a RE process the semantics to the geometry. Actually many researches are discussed the importance of knowledge management of RE. For example, Mohaghegh et al. [2] propose to involve a pre-knowledge on the part before performing the reverse engineering activities. The works of Fisher [3] explore the possibility to extract features even in very noisy data and that by using “knowledge based” techniques. To select surface types and manufacturing actions, he exploits engineering knowledge and functional constraints with some user assistance. Or in their works, the knowledge is implicit and is not driven by a methodology. Thus, the KBE for reverse engineering context is a good solution to reverse a part and obtain a CAD part. It is often based on functional knowledge to reverse the part. So, the manufacturing knowledge is not really integrated. In the scientific literature, a CAD model is obtained from points cloud. Then, process planning is redefined from this CAD model. In this case, feature extraction/recognition based approaches are used and often characterized as knowledge based. For instance, Zhou et al. [4] use feature recognition/extraction and feature based design to integrate CAD and CAPP systems. Or, our approach REFM consists in identifying directly the CAPP model from the points cloud. Hence, KBE is used to extract knowledge on manufacturing. These knowledge should be manage and should be integrate in the re-design stage to reach an optimal CAPP model and then to achieve a successful RE process. It is for these reasons that DFM methodologies are more appropriated. More details will be addressed in the full paper.

REFM is a methodology which concerns components that are get out of the product lifecycle. As mentioned above, REFM is a RE methodology that aims to directly define a new process planning of a mechanical part from 3D and knowledge information. So, the inputs points of REFM method are the digitized part and the manufactured part. Figure 1 represents the overall of the methodology.
To recall, all precedent capitalizations of the original product lifecycle are lost. Thus, manufacturing knowledge extraction phase will be based on user’s suppositions. The aim of REFM could be such as the combination of geometrical approaches (segmentation) and aided process planning methodologies (manufacturing knowledge extraction) of design context. The main innovative point of REFM is to develop “manufacturing knowledge extraction” and to define how it is possible to adapt to RE context in this contribution. Figure 2 shows the REFM methodology in details where manufacturing knowledge extraction phase is developed. The different modules used in our methodology will be described in our paper.

![Fig. 1: REFM methodology](image1)

![Fig. 2: REFM methodology in details](image2)

**Conclusion**

This research proposes a new method for re-manufacturing mechanical components. Indeed, industrial companies have to define a new process planning from 3D information. Or, late commercial solutions, such as Geomagic™, RapidForm™ and CATIA™ are more efficient to obtain a CAD model. Nevertheless, the industrial who needs to define a CAPP model redefines the process planning from this CAD model. REFM is a methodology based on DFM approaches and focuses on the milling process. According to the related works, the Ashby et al. [1] classification seems to be a way of resolution. The future REFM system provides a Computer Aided Process Planning (CAPP) model including new manufacturing tree. This tree must be selected by optimizing the manufacturing sequence and define alternatives operations which aim to facilitate and optimize the re-manufacturing. Each milling operation is a Skin and Skeleton feature [5] which is fitted in the 3D identification.

**References**


Extended Abstract 99

Title:
Digital Human Models and Virtual Ergonomics to Improve Maintainability

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Keywords
Design for Maintenance, Digital Human Modeling, ergonomic analysis, refrigeration unit

Introduction
Maintenance is one of the key drivers for future company success, due to the fact that operations are strictly related to human labor cost [3],[5]. Furthermore in the last decades, standards and laws regarding safety and ergonomic on the workplace have been taking more and more importance. Thus, it is plain and clear how important is to simulate and forecast the impact of maintenance operations on workers [2].
Actually, Design for Maintenance, since early stages of product life cycle outlines the needs and tasks of maintainers in order to reduce time and cost, decreases the complexity of procedures while achieving a higher standard of workers’ conditions.

By the way, DFM prescriptions consist in a set of high level guidelines that engineers must accomplish, but no practical indication are given in order to turn such prescription into real actions [4]. To fill out this gap we have been working on methods integration and now we are able to provide the designers with a structured approach they can follow step by step. The approach relies on the introduction of Digital Human Modeling tools [1],[6], i.e., modeling of the human body that definitively changes any traditional empiric procedure and allows a detailed simulation of body behavior and the interaction with external objects. To analyze maintenance activities we selected a digital human tool belonging to the family of those specifically dedicated to ergonomics: Siemens Jack.

In this paper we show the application of the new approach to a case study related to maintenance operations of a compressor unit used for commercial refrigeration in supermarkets.

Approach and application to case study
This paragraph describes the approach used and briefly shows its application to the compression system.

In the specific case study the main aspects we explored were related to visibility and reachability of workplace during operations and postures assumed by workers assessed by means of Lower Back Analysis (LBA) and OWAS. LBA evaluates the spinal forces acting on a virtual human’s lower back under any posture and loading condition, while OWAS provides a method for quickly checking the comfort of working postures and determining the urgency of taking corrective measures in case of need.

According to the approach we proposed 4 different postures (derived from standard postures, Figure 1) and we not only positioned the virtual humans frontally to the machine but, for each posture, also a 45° and 90° rotation has been done in order to explore a wider range of conditions.

![Figure 1. Standard postures selected.](image)

Afterwards, we evaluated the most frequent maintenance operations that workers have to deal with. According to company’s technicians the copper pipes can be damaged by vibration in the areas where weldments are made manually.
For this reason we decided to simulate the welding activity and in particular those done in particularly uncomfortable positions for operators. Figure 2 shows an example of a weldment area located in the lower part of the refrigerator unit.

![Figure 2. Working space for welding simulation.](image)

Once chosen the postures and the percentiles, the study has been structured in order to evaluate visibility, reachability, verification of operation feasibility and postural analysis.

Visibility has been investigated using the eye view cone, which allows understanding if the working area is visible or not in any different position the virtual human is positioned: three different typology of zones, related to the quality of the vision are defined and used to assess product visibility. Reachability analysis depicts the areas of maximum and comfortable reachability for the virtual humans related to the area interested by the weldment activity.

To take into account comfort we defined the maximum area of extension taking into account the movement and constraints of different body segments.

Moreover, it has been analyzed the feasibility of the operation together with the most interesting postures. For the case study we simulate the act of welding holding a welding torch on the right hand in order to evaluate the possible obstructions and collisions with high temperature components of the compressor unit.

The last analysis concerned the postural sustainability of the most performing working scenario. This has been investigated using lower back analysis and determining Owas class.

**Conclusions**

This work shows a new approach based on the use of Digital Human Models within product design and, in particular, oriented to the fulfillment of maintenance prescriptions. This approach is meant to fill the gap between the theory of Design for Maintenance and high level recommendations, and the everyday need of practical tools and procedures of designers. The structured introduction of a simulation tool for virtual ergonomics allows performing quick analysis in the first phases of product development each time a new product is designed or improved. For instance, in the case study the results achieved could be used for short term modifications (e.g., a review of the workspace requirements for customers to allow workers performing certain task in determined postures), or to be used in case of a complete re-design of the machine (e.g., new layout of the machine taking into account of accessibility of parts to be handled during maintenance operations).

The use of DHM in most cases let unexpected results emerge so that immediate changes can be made to the product or process. For instance, concerning the case study, it is a common belief that big and tall workers are required for hard works, such as maintenance of compressors units of supermarket. On the contrary DHM simulations showed that it is not true in general and for several task the man of the 50 percentile is more suitable rather than the 75 or the 95 percentile.

Finally, the company is willing to introduce the simulation of human tasks and interaction with machine across the entire design department and this explorative study let us foresee that huge benefits are potentially reachable in the area of maintenance of devices that are design not to stop for several years consecutively.

**Acknowledgements**

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References


Extended Abstract 101

Title
A method to analyze 2D vector floor plan and reconstruct 3D models

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Keywords
3D reconstruction, vector floor plan, space information

Introduction
2D architectural floor plans are a standard way to express design by architects and are widely used in the field of architecture, but they are not intuitive. 3D building models are intuitive and also support applications such as photorealistic rendering, building assessment. So conversion of 2D floor plans into 3D models automatically is of great significance.

Some researchers have analyzed 2D vector floor plans and generated topological relations based on layer semantic information [1]. Others reconstructed 3D models from 2D vector floor plan [3] or construction structure drawings [4] [5]. Such methods have problems including strict restrictions on inputs, time-consuming for reconstruction and complex user interaction. The method we proposed in this paper can get the topological and semantic information of spaces as well as generate 3D models very quickly after analyzing 2D architectural floor plans.

Main Idea
A building in real life is usually composed of many functional spaces, such as rooms, corridors, etc. Functional spaces are separated by walls, and openings such as doors and windows. Corresponding to the 2D architectural floor plan, functional spaces are presented by loops which are made up of wall lines and openings. So, reconstructing a 2D architectural floor plan to 3D model has three main tasks: 1) recognizing component symbols such as walls, doors, windows; 2) loop searching to get space information; 3) extrusion to get the finally 3D models. We recognize decorative components using the symbol recognition algorithm based on key features Guo [2] proposed. For structural components, this paper proposes a method based on shape-opening-graph.

Walls, as special building components, are usually made up of two parallel lines (PP). However, there are still a large number of parallel lines such as dimensions and lines of furniture disturbing the wall recognition. We cannot use ordinary symbol recognition algorithm to identify walls. Through analysis of wall lines, we find that a wall either intersects with other walls or adjoins openings. There are mainly three shapes at the intersection of walls: L, T, X [5]. We find another shape I which is actually a wall segment not intersecting with other walls. The I shape is represented as a rectangle which is made up of two pairs of PP intersecting at the endpoints of each PP line. The four types of wall shapes and openings are known as basic elements. Between the basic elements there are three relationships: shape and shape intersecting, shape and opening adjacent, opening and opening adjacent.

Each basic element has adjacent basic elements, so openings that are already recognized can be used to identify walls. We introduce the Shape-Opening Graph SOG = (N, E). Vertices in the graph are one-to-one corresponding to the basic elements and edges are the relationships between them. The graph generation process is the process of identifying walls as well as building the topological relationships between walls and openings. First, select any of the recognized openings as the initial node of SOG. Then the connected region which the opening is in can be obtained according to the relations between the basic elements. Recursive these two processes until all the openings are added to SOG. The PPs of each shape added to SOG are wall lines.

Spaces are represented by loops which are made up of wall lines in 2D floor plan. But walls lines are cut off by openings. We need to use Wall Equivalent Lines (WELs) to replace openings in order to get all the loops. A WEL is two parallel wall lines which connect the two closest walls of the opening. Loops of spaces (rooms, corridors, outer contour), wall contour (redundant loops) and loops having no semantic information (error loops) can be obtained if searching loops directly among wall lines and WELs. Only loops of spaces are wanted and the other two types of loops are redundant. In this paper, we undertake preprocessing to ensure that every wall line only exists in one loop and all the finding loops are spaces having semantic meanings. There exist intersections on one wall line if other wall lines intersect with it. The non-endpoint intersection is called InnerPoint. According to the parity of the number of InnerPoints on each wall line, we
propose the odd-even-breaking edge method. For the odd situation, there must be an InnerPoint wall thickness away from one of the endpoints of the wall line. The breaking method replaces the endpoint with the InnerPoint. For the even situations, there are two cases. One is that two of the InnerPoints are wall thickness away from the two endpoints of the wall line respectively. The breaking method replaces the two endpoints with the two intersections respectively. The other is that two of the InnerPoints are wall thickness away from each other. The breaking method breaks the wall line into two lines whose endpoints are: one of the two InnerPoints, the original wall line’s endpoint closer to the InnerPoint. After the method, the degree of each endpoint of every wall line is 2 and wall lines intersect only at their endpoints.

After preprocessing, there are two kinds of loops in the floor plan: inner loop, which indicates spaces, typically rooms and corridors, and the outer contour. Because the degree of each vertex is 2, using any vertex that has not been traversed as the first vertex, travelling in the counterclockwise direction, all the loops can be obtained. The loop containing the minimum value of x or y is the outer loop. With the text in the drawing, we can get the semantic meaning of each space. We use a hierarchical component tree to describe the topological relations of the building and the root is the building itself. The second layer of the tree is semantic spaces such as rooms and corridors. Each space contains its adjacent spaces. The loops, in which the two wall lines of each PP are, are adjacent spaces. Adjacent spaces are connected with openings. The third layer of the tree is walls and openings. Each wall contains the openings in it. The hierarchy tree can generate the target path for roaming users. The 3D model can be generated after extruding the loops to the wall height and cutting openings from the walls.

![Fig. 1: An example of processing a floor plan. (a) input floor plan (b) the recognized walls, (c) wall equivalent lines, (d)inner and outer loops, and (e)the final 3D model.](image)

We can also construct multi-floor 3D models after analyzing the 2D architectural drawing of its floors by matching their axes in the drawing. Every floor is aligned to the first floor by matching their axes in the drawing.

Conclusions

In this paper, we present a method to analyze 2D architectural floor plans, get the topological and semantic information of spaces and reconstruct the corresponding 3D models.

The reconstruction process is very fast and it can reconstruct a floor plan containing thousands of geometric primitives in several minutes because of using the loop extruding method rather than extruding each wall separately. As we analyzed in the earlier section, the time complexity of reconstructing a floor plan is O(N^2). The working space needed for the reconstruction is O(N). Second, the 3D reconstructed model contains not only geological but also semantic information, the comprehensive structure information of buildings can help the research of other related work. Moreover, the topological information of the whole building are generated using a tree. The topological tree can be put to other architectural software such as REVIT to generate 3D models. Finally, multi-storey building can make the overall structure of the building more clearly unfolded.

References


Extended Abstract 106

Title
Computer-aided dental setup simulation for orthodontic treatment

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Keywords
Digital orthodontic treatment, tooth axis definition, virtual setup planning.

Introduction
In traditional treatment, the dentist needs to copy the arch with a plaster model in order to completely record the patient’s oral geometry. Then, special tools are used to measure teeth width, arch space, and so on. For the treatment setup, the individual tooth needs to be separated from the base and rearranged on the wax mold for planning. The traditional correction method, however, has a number of shortcomings, such as inaccurate measurement and unquantifiable tooth displacement. These issues will affect the quality of the correction, so traditional orthodontic treatment still relies excessively on the dentist’s clinical experience. Conversely, the digital correction method is displayed by the plaster model using computer graphics technology. The physical model can be digitized by a 3D scanner and planned with software. There is almost no choke point for digital measurement, and complete oral information can be obtained. The digital setup assists the dentist to align teeth efficiently and confirm the differences before and after planning. Over the past few years, with the development of CADCAM technology, a lot of research has focused on the development of a dental CAD/CAM system. However, digital setup is still an open issue. Hence, this paper presents a fast and intuitive digital setup system integrating the dentist’s knowhow and computer graphics to achieve rapid tooth arrangement.

Main Idea
This paper proposes a quick setup function which can arrange teeth efficiently. The proposed method is integrated traditional setup know-how and computer graphic technology. Hence, before setup planning, we need to make some related settings in advance, including the teeth axis definition, torque setting and orthodontic wire selection. After preparation finish, the quick setup algorithm can be used to arrange teeth.

1. PREPARATION OF SETUP
   A. Tooth axis definition
      Tooth axis definition is used to simulate the real teeth movement. The teeth’s movement can be classified into the mesial-distal side, the labial-lingual side and the vertical side, which are similar to Cartesian coordinate system. Hence, tooth axis definition is used to specify the local coordinates of each tooth, and assists the user to plan more intuitively.
   B. Bracket loads and torque sets
      The purpose of the torque setting is to present the natural appearance of teeth after setup planning. We load a standard profile and allow the doctor to adjust the tooth until the contour matches. The next step is to attach the bracket on the crown. Since the tooth axis is defined, the bracket can be attached on the crown in a default position.
   C. Orthodontic wire selection
      This paper arranges teeth by using orthodontic wire in a way similar to the traditional correction concept. We first define tooth axis and bracket location; then, the setup simulation can be executed by selecting the exact orthodontic wire. The advantage is that the planning process is similar to clinical treatment and hence can help the dentist accurately predict the results of correction.

2. QUICK SETUP
   In the setup process, after the wire is selected based on the oral profile, the user can scale the orthodontic wire to fit the oral profile. The setup concept proposed in this paper is shown in Fig. 6. First of all, we define a plane at the center of the wire in order to maintain the symmetry of the setup result. For each tooth, we can calculate the transformation matrix from the origin to the center and define as $M_j$. Before setup planning, the incline of each tooth which enables the setup result more natural needs to be set and defined as $M_{torque}$. For the bracket setting, $M_{bracket}$ represents the
transformation of bracket from the origin to crown. During setup planning, our goal is to move the bracket along the wire from the end to the middle smoothly. Hence, the transformation matrix of the bracket from the center to the wire can be expressed as $M_{b2w}$. The temporary position of the bracket on the wire can be expressed as:

$$B_{temp} = [M_{b2w}] [M_{bracket}] B_{init}$$  \hfill (1)

where $B_{init}$ is the original position of the bracket. Similarly, the temporary position of the tooth can be:

$$T_{temp} = [M_{b2w}] [M_{torque}] T_{init}$$  \hfill (2)

As shown in Fig. 1, for the incisor setup, the tooth moves gradually from the end of the wire to the middle. Simultaneously, the collision of the incisor and the plane will be detected. When contact happens, the incisor position will be recorded as $T_{final}$. The next tooth can then be loaded and the same algorithm applied until all teeth are neatly listed and the full mouth is accounted for. Fig. 2 shows the final setup result based on the use of this algorithm proposed in this paper.

**Fig. 1:** The concept of quick setup function  \hspace{1cm} **Fig. 2:** The result of setup planning

**Conclusion**

This paper proposes a digital setup system applied to orthodontic treatment planning. The method mainly combines the traditional setup knowhow and CAD/CAM technology to put forward practical digital tooth arrangement as its system. Compared with the traditional procedure, the digital setup process has many advantages, including: model restoration, measurement, setup planning and simulation. Using the proposed system, the technician first has to define the individual dental axis, torque angle and bracket position. Then, the orthodontic wire needs to be selected according to the patient’s oral profile. After preprocessing is finished, disordered teeth can be rearranged and interference eliminated efficiently with our rapid correction algorithm. Finally, occlusal analysis is used to confirm the contacts and validate the setup result.

**References**

Extended Abstract 107

Title
Using Augmented 3D Objects Instead Of Proxies In 3D UIs

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Keywords
Human Computer Interaction, Tangible User Interfaces, Mobile Projectors, Tracking, Calibration

Introduction
An accepted user interface in a CAD-approach is often as important as the available CAD-functionality. Especially in early design steps or when artistic skills are required, traditional design methods are often preferred due to the lack of appropriate input devices. A particular instance of this consists of applications where the design has to be created on the surface of a real world object. Shoe design and automotive interior styling are two examples where the artist uses a given model and creates details on its surface. In a standard computer based approach, a graphical representation of the object is presented to the user and can be modified using typical input devices, such as a mouse or a drawing pad. The reduced working space on the surface has to be compensated by constantly rotating or translating the object. Alternatively, a three-dimensional input device, such as pen with a tracked tip position could be used, but working on a virtual surface without haptic feedback is far from being practical. Also when utilizing a common haptic device, the workspace is very limited and the object must be rotated or translated (e. g. to compensate for the limited workspace) with an additional input device.

A technological different approach is presented by the use of proxy objects. This was introduced by Hinckley et al. [1] to benefit from the user’s familiarity with the objects presented by the proxies. It was later extended by using the actual design object as one proxy, on which the other proxy (e. g. a pen) is used as interaction object [2]. While the tactile feedback of this interaction is near perfection, the attention focus presents a problem. The design can only be visualized on an additional display and thus the user continuously has to switch attention between the real objects and the display. The motivation of a new user interface for such situations is to provide a tactile feedback without workspace limitations even for larger objects, and to allow an augmentation in the original working environment.

Main Idea
We present a novel setup for a CAD-interface using a mobile projector, the physical design object and an input device (which is typically a pen). The moveable projector is attached to the input device or the user himself so that the current workspace can be augmented. The key idea is that the projected image can be adjusted so that the content seems to be fixed on the design object’s surface even when the projector or the design object itself are moved. Our main contributions are:

- interactive and precise surface augmentation on physical, non-flat objects without the need for glasses or HMDs,
- procedures to match virtual computer graphics projection and optical path of the projector to account for surface distortions,
- tracking and calibration setups for projector and various interaction objects.

Projection onto the design object
One major motivation is that the real object is not a display and that a single, fixed projection onto a non-flat surface cannot cover the surface sufficiently. To overcome this limitation, we adjust a mobile projection to the focus of the user, which is in most cases defined by the interaction device. Using a tracking system, we match the computer graphics projection, which is used to create the image from the 3D scene, with that of the projector. As seen in Fig. 1, the computer generated overlay contains additional information, which makes the projector a so called ‘Augmented Reality (AR) Flashlight’.

We identify important requirements which must be fulfilled by a design object in order to be used as projection target in our approach. Those are discussed to allow the reader assessing the applicability of the interface in other design processes.

International CAD Conference and Exhibition, Final Program CAD’13 Volume 10

Page 221 of 226
Fig. 1: Prototype interface for shoe design. A shoe last is used as projection surface and the mobile projector is placed (a) on the interaction device (pen) for drawing design lines or (b) on the user for inspection of the finished design.

Tracking and Calibration
For setting up the virtual scene, we need to track position and orientation of the mobile projector, the design object and the interaction object. Since we do not want to constrain the workspace too much, we employ an optical tracking system which can cover several meters in workspace. A practical approach to calibration without additional markers, patterns or cameras is presented and can easily be implemented by the reader.

Projection setup
In most applications, a pen is the natural input device to the designer. We discuss important factors which influence the attachment of the projector at this input device. Examples are focus settings, size and distance of the projection unit. Additionally, two alternative setups are presented in which the projector is fixed first on a pointing device and second on the user. Practical insights from our prototypes are given.

Application scenarios
Three scenarios are described in which our approach has potential to enhance or create CAD-user interfaces. Shoe design is a prime example of an artistic modeling process in which CAD is not yet playing such an important role as in other design processes. The artistic part takes place only with pen and the shoe last (see Fig. 1) and our idea provides a mean to make computer support accessible to the traditional designer. Other examples discussed are freeform drawing on 3D objects and visual inspection without major limitations of existing interaction approaches.

Evaluation with pilot user study
Since our current research focus is on shoe design, we conducted a pilot user study to estimate the reception of our new approach. For this, we designed three interaction scenarios with similar shoe design tasks. Those scenarios, including a standard interface, a classical tracking-based interface and our novel approach are compared and user feedback is presented.

Conclusions
We introduce a precise augmentation method for non-flat geometries by adjusting a mobile projection to the user’s focus and by using marker tracking technology. The pilot user study has shown great potential of the approach compared to traditional desktop interfaces, but was still influenced by limitations of the prototype setup. The discussion in the paper allows a practical implementation of our approach in a wide range of CAD-applications. Further directions for research and ideas for improvements are given.

References
Extended Abstract 108

Title
CAD Feature Extraction Using Opitz Coding System

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Introduction
Classification and retrieval of product data containing design and manufacturing know-how play a key role in optimization of the product design in the first stage of the design. According to the statistics, more than 75% of engineering design activities addresses reusing of the previous design knowledge for designing of a new product [4]. In the other side, cost of the design changes of product development increases exceedingly by the time of development. It is essential to support the designer in the decision process and reduce the risk of false decisions which may extremely consume time and cost to be corrected afterward. Rozenburg and Eekels [3] show that most of design decisions are made with intuition and simplified decision rules. In this regard, an efficient classification and indexing is proposed to assist the designer to make optimum decisions. Classification and retrieval of the successful previous product design knowledge may lead the designer to an innovative design by increasing his knowledge about the conceptual design of new potential product, in addition to information on manufacturability, process planning, cost, etc. To conclude, with using the design synthesis and analysis of already produced product, it is possible to evaluate the performance of the expected product.

Main Idea
In this research, a manufacturing based structure has been applied for data classification. Using this method offers an innovative procedure to integrate CAD and CAM data. The objective of this research is to apply the extracted features of a 3D CAD design from Initial Graphics Exchange Specifications (IGES) and Boundary Representation (B-Rep) for the design classification. There are several similar researches on feature extraction which aim for enlightening manufacturability or process planning of the previous products in the context of conceptual engineering [1]. The novelty of the current approach regards to classification and indexing of the product information to be reused in a new design from the first stage of design. This methodology is based on feature recognition and extraction of a 3D CAD drawing to be applied for fulfilling a manufacturing-based coding system, so called Opitz coding system. The Opitz coding system is a recognized platform for manufacturing classification. The feature extraction method uses the IGES neutral file format for 3D CAD. In the next paragraphs IGES and Opitz coding system are briefly described.

Initial Graphics Exchange Specifications (IGES) was developed by National Aeronautical and Space Administration and National Bureau of Standards in 1979 and it was recognized immediately by American National Standard Institute (ANSI) [1]. It was developed as a neutral format or data structure for data exchange between unlike CAD/CAM systems while presenting an object oriented data. IGES has the following main characteristics:

- **IGES consist of three types of entities**: Geometric entities to define an object (like arcs, lines and points). Annotation entities for documentation and visualization of an object (like dimensions and notes). Structure entities to define the associations between other entities in IGES file.
- **IGES file consists of five sections**: Start section, Global section, Directory Entry (DE) section, Parameter Data (PD) section, and Terminate section.
- **IGES format**: IGES file is written in ASCII format and it is formed of 80 characters.

The IGES file of a CAD drawing can be considered as a structured data format for CAD model, however, the raw data of a CAD drawing. Therefore the information of IGES can be extracted and tailored for any specific feature recognition.

The Opitz coding system was introduced by Herwart Opitz, professor of machine tools and production engineering from Technical University of Aachen in Germany [2]. It is a well known classification method used in manufacturing composed of 13 digits. The Opitz classification system has been widely used in manufacturing since then. Opitz code is composed of thirteen primary digits to convey the design and manufacturing information of a part and the digits are

*International CAD Conference and Exhibition, Final Program CAD’13 Volume 10*
divided to three sections. The first five digits called ‘form code’ which presents the design attributes. The second four digits or the ‘supplementary codes’ are reserved to indicate some of the manufacturing attributes. Third section or ‘secondary code’ is an extra four digits to be fulfilled with 10 possibilities indicated with numbers from 0 to 9 based on the distinguished feature of a part. Only the ‘form code’ is able to classify and differentiate between $10^5$ manufacturing models.

The developed method uses IGES file of the CAD model to construct the related B-Rep model. Subsequently, the feature recognition and extraction method receives the input from B-Rep model. Finally based on the Opitz coding system and definition, the required features are extracted to construct the associated Opitz code. Fig. 1 represents the different stages of building an Opitz code for a 3D CAD model.

**Conclusions**

In this research, The Opitz coding system has been selected for classification and standardization of the geometrical and topological information of a CAD model. The ultimate goal of the feature classification in this context is knowledge retrieval and reuse. It is assumed that the knowledge about a product is inherited in its features. Consequently, feature classification and indexing is the first level of the product knowledge transmission. In the next level, to improve the quality of the indexing, the extension of Opitz coding system is required to include more characteristics of a product.

**References**


