A Two-User Framework for Rapid Immersive Full Cycle Product Customization

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Abstract. In this paper we present an approach for a full cycle product customization in Virtual Environments (VE). The main goal of our work is to develop an integrated immersive framework, which allows configuring products from a great number of parts. Our framework supports collaborative work of two users and operates both on desktop computers and in immersive environments. The framework is integrated into a manufacturing environment, thus making the immediate production of customized products possible. The integrated modules of the framework allow importing CAD files directly into VE, creation of new objects on the basis of constructive solid geometry principles, attaching virtual connectivity-describing attributes to parts, guided assembly of parts and comprehensive analysis of products. In order to identify the influence of immersion and collaboration on the performance in assembly and manipulation tasks in VE, we performed a quantitative assessment of user performance, which we also describe in the paper.

Keywords: Virtual Environment, Mass Customization, Product Development.

1 Introduction

The research on Virtual Reality (VR) technology and its applications in manufacturing industry has been actively performed during the last 15 years. Automotive companies, such as GM, Daimler-Chrysler and BMW [3], use VR applications in their production pipeline, but the technology as such is not yet fully integrated into the workflow and production process of most manufacturing enterprises. There are 3 main reasons for that. First of all, the hardware prices of VR installations have been quite high and became affordable only recently. Second, data formats used in VR applications were usually not compatible with common Computer-Aided Design (CAD) software and thereby prevented a seamless integration with traditional business processes. Third, the interfaces of VR applications have been quite complex, while their functional possibilities were limited and inflexible.

The European research project INT-MANUS [6] investigated between 2005 and 2008 the improvement potentials of flexibility and adaptability of manufacturing systems. The core technology of INT-MANUS is the Smart-Connected-Control platform (SCCP) [22], which integrates machines, robots and human personnel. The

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platform provides numerous services and provides specific interfaces for monitoring, controlling and configuring a production environment. Among other INT-MANUS achievements, we have developed a full cycle product customization framework for 3-D VR-based systems, which we present in this paper. The main purpose of this framework is to allow the configuration of products from a great number of parts, which can be modeled, attributed and assembled directly in the immersive environment and scheduled for immediate production. The framework is directly connected to the INT-MANUS SCCP platform, which allows automatic production rescheduling in response to configuration changes made in the framework.

Our framework combines two-dimensional menus with immersive three-dimensional widgets for a more effective interaction. It allows the team-work of two users not only by using special collaborative techniques, but also by providing correct 3-D perspective for each of the two co-workers. The framework can be used on desktop computers, although a two-user projection-based Virtual Environment allows a more effective benefit from the framework‘s potential. In the next sections we describe the related work and present the framework architecture and its modules.

2 Related Work

Virtual Prototyping is used to simulate assembly and to evaluate prototypes in different design stages [20]. It assists customized production development by virtual manufacturing simulation and visual evaluation on the basis of Virtual Reality technology, which generates 3-D immersive interactive worlds.

A part of manufacturing simulation is the assembly simulation, which involves packaging issues as well as determining required space regions by calculating assembly paths for parts. Several assembly simulation systems have been developed in the recent years [2, 9, 10, 11, 15, 21, 23, 27]. These simulation systems use physical-based [2, 9, 21, 27] or knowledge-based assembly constraints [10, 11, 15], as well as a combination of both [23]. Some systems have been developed for head-mounted displays [9, 15, 21, 27], while others used projection-based display systems [2, 10, 11, 23]. For example, Zachmann and Rettig [27] presented multimodal and spatial interaction for virtual assembly simulation and considered criteria like naturalness, robustness and precision for the development of grasping techniques and gestural input. Multimodal assembly and the extraction of connection properties from CAD files have been studied in [2]. The VADE system [9] is a fairly complex assembly simulation environment, which uses CAD models to represent the assembly area. Ma et al. [15] proposed a hierarchical-structured data model on the basis of positional relationships of feature elements.

A group of contributions focused on immersive modeling applications that support the assembly of complex models out of predefined parts. Jung [10] represents the connection sensitivity of part regions using so-called ports. From the rich connection semantics of those the constraints for part connections are derived. This includes analyzing the geometric relationships among the involved parts and allows finding a solution even for complex port configurations on multiple parts. The VLEGO modeler [11] allows assembling toys from blocks. Arising from the properties of those blocks and their studs, VLEGO restricts possible connections of blocks to discrete positions and orientations.

Collaborative object manipulation for two users wearing an HMD has been investigated by Pinho et al. [18]. They presented two kinds of collaborative manipulation tools; one is based on the separation of degrees of freedom for two users, whereas the other relies on the composition of user actions. They have observed increased performance and usability in difficult manipulation tasks. Another example of collaborative VE is the SeamlessDesign system of Kiyokawa et al. [12]. The system allows two users to model collaboratively, interactively combining geometric primitives with constraining primitives.

The integration between VR and CAD systems is an important issue [4, 7]. The aim of these researches is to allow modification of CAD-imported objects within Virtual Environments, in such a way that it becomes possible to reflect the modifications done in VR back to the CAD data. The coupling between VR and CAD functionality in both systems is done with OpenCascade technology[1], although the same approach can be also applied to more widely used CAD systems, such as CATIA [4].

The research on the benefits of VR technologies allows to understand better, in which tasks VR can be especially useful and how exactly it should be applied. For example, Zhang et al. [28] found out that the assembly task performance can be improved by visual and auditory feedback mechanisms. However, the hypothesis on the positive effects of immersion and natural 3D interaction for affective analysis of product design has been rejected [14]. Ye et al. [26] compared immersive VR, non-immersive desktop VR and traditional engineering environment in assembly planning tasks. He found out that performance time in the traditional environment was significantly longer than one in the desktop VR, and that the difference between the desktop VR and immersive VR was not significant.

Narayan et al. [16] investigated the effects of immersion on team performance in a collaborative environment for spatially separated users. He noticed that stereoscopic vision had a significant effect on team performance, unlike head tracking, which had no notable effect on the performance at all.

There are many user studies that compare the performance of different display systems for very simple object manipulation tasks. The results achieved so far are inconsistent and seem to depend on the kind of task to be performed [5, 24], although the effect of large displays is considered beneficial [17].

3 Framework Architecture and Its Use Cases

The pipeline of our product customization framework is presented in Fig.1. It consists of the following stages: import or immersive creation of product parts (1), visual attributing the parts with connection semantics (2) and interactive assembly of the virtual product from the part set (3).

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[1] http://opencascade.org

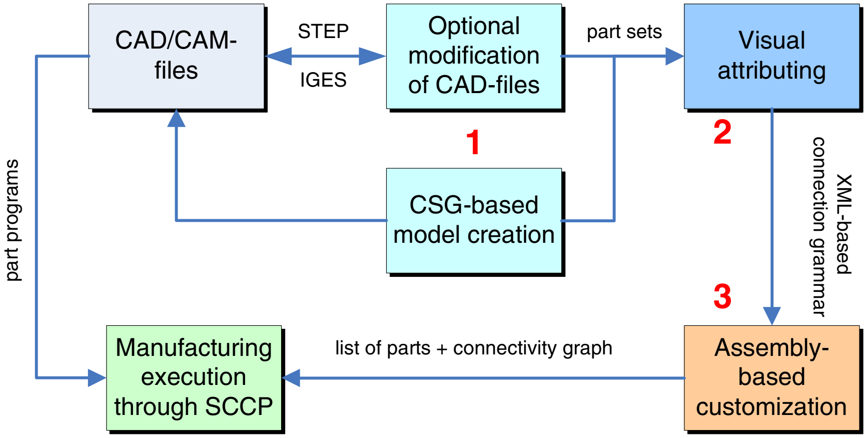

Fig. 1. The product customization pipeline

For a better understanding of the framework we want to consider an example – a company that produces complex products consisting of multiple parts in different variations. The company manufactures multiple product variants depending on the market situation or customer needs. The company may use our framework for the following purposes:

1. collaborative design evaluation in the immersive environment with possibilities to modify original CAD data and to create new 3-D objects from primitives on the basis of Boolean operations,
2. collaborative and interactive creation of connectivity semantics to simplify and guide assembly customization,
3. collaborative customization and evaluation of products by assembling them from great number of parts on the basis of the connectivity semantics,
4. supervised assembly training,
5. scheduling of production by sending the list of selected parts and their connectivity information to the manufacturing execution system through the SCCP platform.

Different collaboration modes are supported by the framework. For example, collaborative design evaluation would require a team-work of a designer and an engineer, while collaborative product assembly could be done with an engineer and a customer. Thus, the framework supports different roles, which define the functionalities available for a user.

The user interface of the framework is fully integrated into the immersive environment and uses context-based adapted two-dimensional menus as well as three-dimensional widgets for system control tasks. The widgets move functionality directly onto objects, allowing the exploitation of the full degrees of freedom of the three-dimensional workspace. The interface supports selection and manipulation of individual objects as well as groups of objects.

Our framework is based on the virtual reality framework Avango® [13], which supports different display systems from single-user desktop to multi-user projection-based virtual environments. We used the TwoView Virtual Environment [19], which supports independent head-tracked stereo viewing for two persons. Up to five persons can work with the systems simultaneously, but only two of them will see images with correct perspective projection. The TwoView display system consists of two active-stereo-capable DLP projectors behind a vertical 3 m x 2.4 m screen. Two simultaneously displayed stereo image pairs are separated by polarization filters in front of the projector lenses. The shutter glasses have corresponding filters, so that each user sees perceptively correct active stereo projection. The display system is integrated with an optical tracking system based on passive markers, which are attached to shutter-glasses and wireless interaction devices.

4 Part Import and Immersive Creation

Our framework allows importing part models from various standard CAD-formats that are frequently used in the industry, such as STEP or IGES. A new object can be directly created and modified in the immersive environment by applying constructive solid geometry (CSG) operations to geometrical primitives or imported models (see Fig. 2).

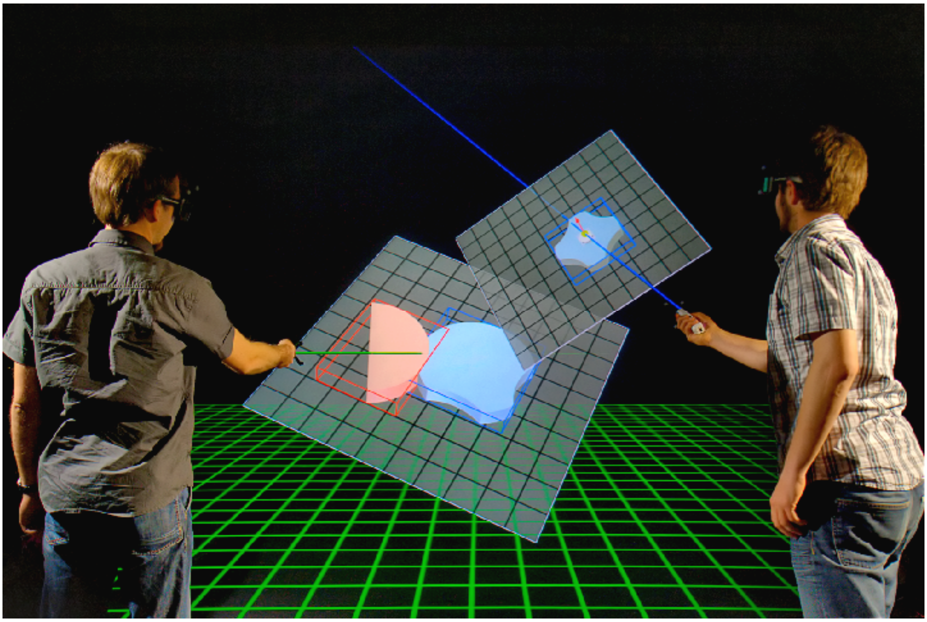

Fig. 2. Collaborative CSG-based creation of models in the TwoView Virtual Environment

The operations hierarchically combine objects on the basis of set operations like union, intersection and difference. Similar to [4, 7], our framework uses the OpenCASCADE geometric kernel to perform such operations. At the end of this activity, users can create sets of parts that may be connected together to form a product and save them in separate XML-based files. If geometry has been changed or created newly, the framework will send the new CAD file to the SCCP platform, which will create a request to produce respective part programs for manufacturing machines.

5 Visual Attributing with Connection Semantics

Our framework employs knowledge-based assembly constraints in the form of a grammar, which encodes the semantic connection information of all part models. The grammar is based on the concept of so-called *handles* [8]. These virtual objects can be directly attached to all parts in the immersive environment and configured to describe their connection semantics. Handles use geometric primitives, like points, vectors and coordinate systems. They have two main purposes: first, handles define the set of models constructible out of the set of given parts; second, handles support users by guiding them in the assembly process. Two parts can be connected at a common location if there is at least one pair of matching handles from each part.

Accurate positioning of handles in Virtual Environment is a challenging task, which requires visual guidance from the VE. We suggest the following assisting strategies, which should help a user of our framework to find optimal handle positions:

1. When requested, our system calculates a map of normals for all vertices of a 3-D model. The user can associate a handle with a normal, and move it along the surface (Fig. 3, left). In this case the accuracy of handle positioning is limited by the normal map sampling rate.
2. If the handle has to be positioned more accurately, the user can use assisting flat grids with variable size and sampling. This allows handle positioning with arbitrary accuracy in the coordinate system of the 3-D model (Fig. 3, right). This method is especially suited for flat surfaces.
3. Our system can also calculate assisting points of interests, such as the center of mass or the center of a flat geometrical primitive, which can help the user in estimating best positions for handles.
4. If two parts have to be marked as compatible and the positioning of handles is not important, the user simply moves the parts close together, and the framework calculates two normals with minimal distance for both adjacent surfaces and marks them as handles.

The strategies mentioned above rely on the polygonal mesh of a part, which actually is an approximation of the exact surface equation obtained by point sampling, i.e. by tessellation. In case the manufacturing process needs exact positioning of handles on the surface, we have to take the restrictions of existing strategies into account and apply additional ones, when necessary. If the vertices of a polygonal mesh coincide with the exact surface, handle placement only at these locations is exact. Arbitrary handle positioning on a curved or spherical surface can be achieved using the following additional strategies, which we are currently investigating:

1. In case of parametric surfaces, the parametric domain can be used as an assisting grid (see method 2 above) and mapped to the surface, so that the user can snap handles to exact surface positions.

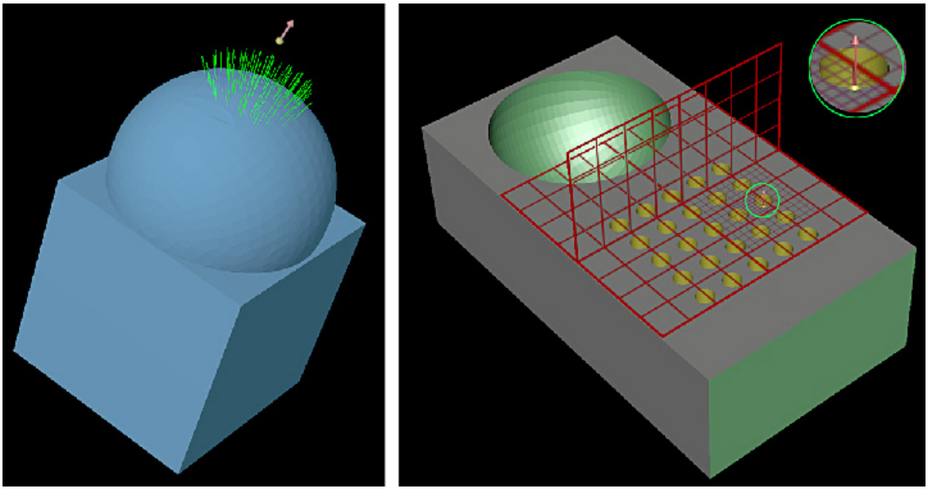

Fig. 3. Assisting strategies for handle positioning: map of normals in the vicinity of the handle (left) and assisting grids (right)

2. In case of implicit surfaces, the user can place handles exactly on the surface based on ray intersections.
3. For interactive searching for handle positions, the user can probe the surface and, based on the surface equation, can get information on the features of the surface, e.g. coordinate values, certain points like center points or mid-points, local extreme points, etc. Such positions are in many cases candidates for connecting other parts.

The output of this module is the XML-based file effectively describing possible set of part combinations, which may form the product. Additional information, such as time and costs needed for production of a part, can also be added to the grammar.

6 Assembly-Based Customization

The XML-based grammar produced in the previous steps to create part sets and constrain their connections is used as the basis for assembly-based product customization.

In addition to the selection and manipulation techniques mentioned above, this module of the framework supports the following tasks:

1. Add parts to the scene and remove them using drag-and-drop technique.
2. Assemble and disassemble compatible parts. As recommended in [28], the framework visually reacts on the actions of the user. When two parts with compatible handles are moved close enough to each other, the handles are highlighted. If the user continues bringing parts together, they will be automatically connected with the handles (snapped) and highlighted for a short time.
3. Visual inspection of parts, part groups and their connections. The user may alter material properties (textures), part transparencies and global illumination. In addition to that, the user sees the time and cost needed for production of a part group. However, the total production time is simply the sum of production times of all components, and the actual time may vary depending on parallelization.

4. Finally, assembled configurations may be saved and scheduled for production by sending the assembly graph containing the set of parts needed for production, their properties and connectivity information to the SCCP platform.
   The details of this framework module may be found in [1].

7 Comparative Assessment of User Performance

In order to identify the influence of immersion and collaboration on the performance in assembly and manipulation tasks in a virtual environment, we performed a quantitative assessment of user performance in an assembly modeling application on the basis of our framework. We asked each of twenty participants to perform a specific task ten times in four modes: in single and collaborative two-user modes with stereoscopic and monoscopic vision for each mode. The participants had to assemble a table out of a table plate and four table legs and place it at a specific position on a floor plate. In each assembly task, the modeling parts were randomly positioned in space, while the sum of the inter-object distances was kept constant for all initial configurations. An automatic timer clock measured and logged the task completion times, starting with first and stopping with last assembly operations.

The results showed average speed-up factors of 1.6 and 1.4 for collaborative interaction and stereoscopic vision respectively. With both collaboration and stereo vision the performance of users could be increased by factor 2.2. Interestingly, early experiments on quantitative estimation of stereo vision benefits [25] showed that stereo allowed increasing the size of understandable abstract data in VE by factor 1.6, which is quite close to our results, despite the fact that the tasks are completely different. More details about our comparative assessment may be found in [1].

8 Conclusion and Future Work

We have shown that the immersive environment may be effectively used for a full cycle product customization: from creation of individual parts to scheduling of complete products. We described the coupling between VR environment and CAD functionality, the grammar-based assembly constraint and assembly-based product customization. The developed framework may be used in any production environment and can be easily adapted to different immersive display systems. The framework has also been used to evaluate the benefits of immersion and collaboration on task performance in assembly and manipulation operations. The results of the evaluation allowed measuring the benefits of stereoscopic vision and collaboration in Virtual Environments quantitatively. In our future work we are going to develop more sophisticated collaborative interaction techniques, integrate different interaction and haptic devices into the framework, and implement application-specific widgets to improve 3-D interaction.

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