Virtual prototyping for customized product development

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Customized product development is facing the challenges of maintaining mass producibility and exploring customer perception on target products. This paper reports an approach by combining virtual prototyping (VP) with design by manufacturing simulation techniques. By constructing virtual prototypes, accurate assessments of mass producibility and customer acceptance will enable better informed design of customized products. The primary goal of VP for customized product development is to provide a multidisciplinary design definition and rapid prototyping environment for concept development and a tailored, scenario-based simulation environment for concept evaluation within a single facility. This design environment facilitates the capture and utilization of information generated during the design phase, and the simultaneous generation, at design time, of manufacturing, materials, costing, and scheduling data, together with visual evaluation of customer perception on target products, hence supporting the implementation of concurrent engineering.

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1. Introduction

In an age when consumers demand high-quality, low-priced and customized products, the competition among firms has ceased to be strictly a price competition and is now a competition in product variety and speed to market (Pine, 1993). The current philosophy is to replace old products constantly with either an improved product or a new variation of the product. Differentiation in product variety, i.e. customization, assumes ever increasing importance as a marketing instrument. The duration of a product's life depends on its acceptance by the consumers; a "failed" product could be out of the market in a matter of months. A short product development cycle is crucial to the survival of the company as it enables the company to deliver new products to the market quickly. On the other hand, pursuing variety and quick response would not compromise the economy of scale, an advantage characterized by mass production. The balance between the economy of scale and scope is often difficult as manufacturers pursue a "dynamic stability" (Boynton and Bert, 1991).

Customization emphasizes the uniqueness of the products. This product proliferation naturally results in the continuous accretion of variety and thus engenders design variations and process changeovers. This situation contradicts the pursuit of the low costs of mass production where flexibility is limited and stability is emphasized. Such a setup, therefore, presents product development with a special challenge. It is vital to provide designers with feedback from production, quality, and tests early at the conceptual stage so as to maintain the integrity of the product family and the continuity of the infrastructure, hence leveraging existing design and manufacturing investments.

Concurrent engineering (CE), as one approach to these problems, is well recognized with its natural focus on product design (Prasad, 1996). CE calls for the consideration and inclusion of product life cycle concerns such as aesthetics, ergonomics, marketability, and manufacturability in the product design process. In CE implementation, the link between designs, represented as geometric information, and manufacturing instructions has been a major obstacle to CAD/CAM integration (Choi and Barash, 1985). A number of techniques have been developed to bridge this gap, including feature-based design and feature extraction approaches. Aiming at the challenge of keeping the economy of scale, this paper adopts an alternative approach, called design by manufacturing simulation (DMS). The concept that manufacturing simulation could be used as a design tool was first introduced by Gossard (1975). In his approach, parts are designed by simulating manufacturing operations on the screen; thus, designers generate manufacturing specifications as they design. Simulation based design (SBD) is a similar approach popularized by successful DARPA (Defense Advanced Research Projects Agency) initiatives in the early 1990s (DARPA, 1994). SBD refers to the use of computer simulation techniques for system design using virtual prototyping models. Simulation of virtual prototype design is accomplished through the construction of a virtual system prototype and virtual environments (Karangelen and Hoang, 1994).

On the other hand, a number of marketing studies (Berkowitz, 1987; LaChance-Porter, 1993; Sujan and Dekleva, 1987) have pointed out the significance of understanding customer preferences on the appearances of new products. An attractive appearance draws customers to a product and adds value to the product by increasing the quality of the user's experiences (Kotler and Rath, 1984). Therefore, identifying those elements that enhance the chances for customer's acceptance represents an important issue for engineering designers. With this in mind, effective use of customer preference data in engineering design helps integrate the perspectives of marketing professionals and designers.

As for a product's appearance, customer reactions appear to depend in part on how well the design conforms to aesthetic principles such as those developed by Gestalt theorists (Veryzer, 1993) and ergonomics criteria. Preferences also may be affected by how well a new design fits within the constellation of existing designs. Therefore, the ease with which customers may categorize a new design and its closeness to existing prototypes may play a significant role in marketplace acceptance (Sujan and Dekleva, 1987). Although Gestalt and prototypicality principles may apply widely to customers, salient individual differences (i.e. customization) in product appearance preferences are possibly expected. As a result, it is important for design teams to explore the customer's perception on the appearance of a target product.

Traditionally, market analysis techniques are adopted to investigate customer responses to design options. For example, conjoint analysis is widely used to measure preferences for different product profiles and to build market simulation models (Dobson and Kalish, 1993). LaChance-Porter (1993) takes a qualitative approach and uses focus groups to provide a reality check on the usefulness of a new product design. However, although a number of researchers agree on the importance of including customer preferences and other marketplace information in product designs, methodologies to capture product preferences and tastes are not evident in a concurrent engineering context (Veryzer, 1993). In other words, it is imperative to integrate both the customer's perception and manufacturing concerns in design evaluation.

This paper reports a research effort of combining virtual prototyping with design by manufacturing simulation techniques so that individual customization requirements and the process capabilities of a company can be balanced in the design stage. Our domain of VP consists of more manufacturing simulation and product visualization than the modeling of interacting physical processes, which is the focus of most other VP investigations. The proposed approach extends traditional applications of VP from product design to including manufacturing and customer exploration. That is, by constructing several virtual prototypes, accurate assessments of mass producibility and customer's acceptance will enable better informed design of customized products.

In the next section, the concept, feasibility and merits of VP are discussed with respect to the requirements of customized product development, along with the key techniques associated with VP. Section 3 presents the considerations on the system architecture and configuration of VP-aided design environment (VPDE) for customized product development. Also discussed are the rationale of VPDE, the integration of VP, design iteration, and engineering analysis, as well as the interfaces between virtual world and physical world and interactions between designers and customers through engineering database. An implementation example is presented in section 4. Finally, discussions and conclusions are drawn in section 5.

2. Virtual prototyping

During product development, physical prototypes are frequently required for iterative evaluation to provide feedback for design modification such as selection of design alternatives, engineering analysis, manufacturing planning and visualization of a product. Even using conventional processes and highly skilled technicians, the time, effort and cost of constructing a prototype are substantial (Gibson *et al.*, 1993). Rapid Prototyping (RP) systems are capable of making highly accurate prototypes in a short time. The starting point for such systems is good quality 3D CAD modeling where solid models are constructed and then post-processed in a layer format, using, for instance, stereolithography, to make them suitable for the prototyping machines (Jacobs, 1992).

Improvements in the use of rapid prototyping have been discussed in design visualization, product functionality verification, iterative development, and testing for optimization (Jacobs, 1992). There seems then to be some obvious overlap with the potential attributes of virtual reality (VR) (Burdea and Coiffet, 1994) for product design. Intuitively VR could be used interactively with rapid prototyping technologies to enable even more effective use of RP and better planning through very early visualization, fit and functionality testing. Gibson *et al.* (1993) reported VR+RP had something different to offer and the notion of using "digital clay" allowed fuller and faster exploration of functional, aesthetic, and ergonomics design criteria. Gibson *et al.* (1993) recognize the significant benefits potential through the application of emerging VR and VP technologies for design and manufacturing. The proposed VP environment targets this opportunity directly.

Recent developments in computer graphics and computer simulation have provided more sophisticated tools for electronic prototyping (Burdea and Coiffet, 1994). Specifically, VR techniques offer the possibility to experience virtual worlds with very high realism. Applying VR to electronic prototyping greatly improves the quality of presentation. This intuitive approach to object manipulation opens new opportunities for prototyping based on CAD models. It is possible to take the data model of a product as a virtual prototype instead of a real one to model and analyze geometry, functionality and manufacturability of the designing products interactively (Astheimer and Gobel, 1995).

2.1 Types of prototype

There are basically two types of virtual prototype, i.e. the immersive virtual prototype and the analytical virtual prototype. Recent progress in the development of graphics hardware has allowed complex geometric representations to be rendered and manipulated in real time. These representations, when coupled with new human computer interfaces such as datagloves and headsets, can help give the user a belief that the object actually exists. The virtual effects and tactile properties are of primary importance in these immersive virtual prototypes, which are necessary in visualizing and interacting with the digital clay. A more useful form of virtual prototype, in the context of product development, is one that tells the user how it will perform and behave in its intended environment. This analytical virtual prototype usually uses standard computing technology (mouse, keyboard and screen). It is thought that eventually they will also use immersive technology. Leaving aside the problems of moving toward immersive environments, analytical virtual prototypes will not be used efficiently within the product development process until geometric representations are efficiently integrated with analysis applications. This seems to be a serious problem (Kimura, 1993; Kjellberg and Schmekel, 1991).

2.2 VP-aided design

In VP, a product data model is employed to build a computational prototype (digital mockup), upon which operations and analysis can be performed like its physical representation in the real world. VP-aided design is based on the integration of computer supported modeling, simulation and the presentation of the target products and the related production. As shown in Figure 1, product realization activities are first performed with respect to the virtual world, where all the necessary product data and manufacturing processes are modeled. The interaction between the design world and the virtual world comprises a virtual design environment where product definition, design engineering and manufacturing are integrated together.

2.3 Key techniques associated with VP-aided design of customized products

2.3.1 Product representation and model generation

The comprehensive modeling capability of products and the related engineering activities are essential for VP-aided design, which integrates all product information and bridges different stages of product development. Underlying design and simulation capabilities is the product representation. Product representation must evolve along the design time-line, support design including decision making and concept exploration, and be capable of readily generating simulation models at an appropriate level of detail. Product modeling plays an essential role in product representation and simulation model generation. A product model is a generic model used for representing all types of artifacts that appear in the course of design and manufacturing. It represents target products, their materials and intermediate products, tools and machines, and any other manufacturing resources and production issues (Kimura, 1993). In addition, in order to support downstream manufacturing activities, product representation must be converted from a central (design) representation to a representation suitable for reasoning in a target activity. Computationally efficient methods for recognizing features from solid models (i.e., conversion) have been studied extensively (Choi and Barash, 1985; Kjellberg and Schmekel, 1991). By following similar methods to feature-based component representations, converters can be developed for assembly representations, specifically for generating VP models for engineering analysis.

2.3.2 Human-computer interaction

The distinguishing characteristic of VP is the use of immersion and interaction – a new paradigm in human computer interaction – allowing the designer and/or customer to be sensorially (sight, touch, sound, etc.) immersed in the system being designed using a combination of hardware and software technologies (Burdea and Coiffet, 1994). It is essential that human senses are provided with information that represents the data model as realistically as possible (Astheimer and Gobel, 1995). For this purpose VR techniques are applied to create and exercise virtual prototypes that engage developers and users via visualization and sensory immersion. VR-based presentations make all relevant data visible. The visualization is based on the VR data model, which contains the actual geometry and lighting information generated by the modeling and simulation tools. The interaction interprets user actions and either changes the viewing parameters or generates logical events for simulation and manipulation. The visual evaluation of a prototype by potential customers can contribute to the entire product development process, particularly, in the cases of consumer products that feature aesthetic and ergonomic design criteria.

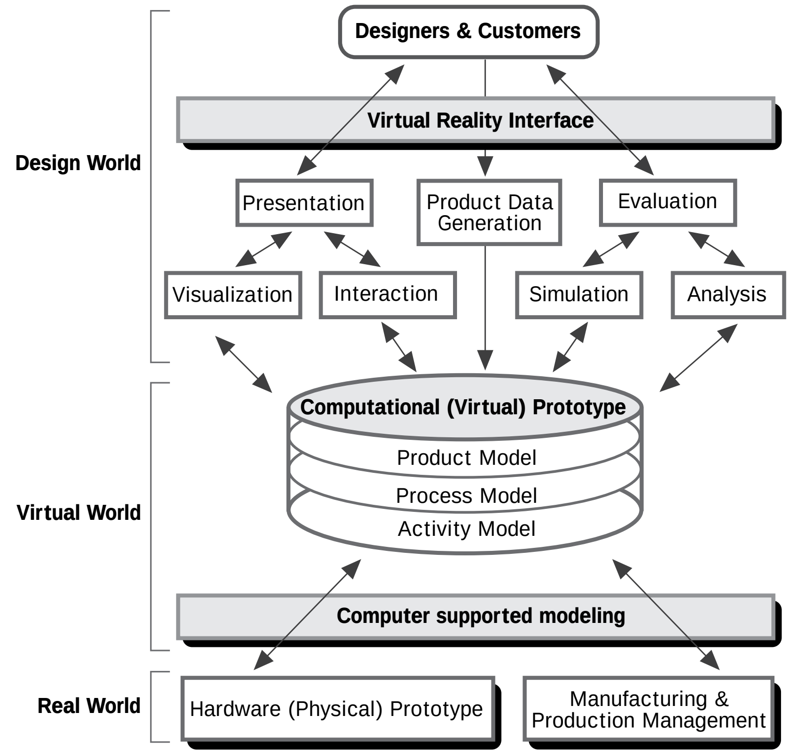
2.3.3 Manufacturing simulation

Design analyses are conducted based on prototype evaluation. Simulations make available the prediction information about the product behavior, manufacturing processes, and production planning, which enables prototype evaluation. As the kernel of computer-aided manufacturing simulation, analytical virtual prototypes must involve process modeling and activity modeling (Kimura, 1993). Process models are used for representing all the physical processes that are required for representing product behavior and manufacturing processes. Activity models represent various engineering activities, whether human or by computer, for product engineering and production management, such as costing and scheduling. Some of the related works are given in Kimura (1993) and Kjellberg and Schmekel (1991).

2.3.4 Product library

To manage product differentiation effectively, a product family architecture (PFA) is necessary for capturing and utilizing commonality among specific products. The PFA consists of well-defined building blocks and configuration structures so as to accommodate diverse customer needs (Tseng and Jiao, 1996). Under the umbrella of a PFA, each new product instantiates and extends so as to anchor future designs to a common product line structure. When PFA is incorporated, VP-aided design not only unburdens the knowledge base from keeping variant forms of the same solution, but also models the design process of a class of products that can widely variegate designs based on individual customization requirements within a coherent framework.

Figure 1
The principle of virtual prototyping-aided design



3. VP-aided design environment

As shown in Figure 2, VP assists customized product development in two aspects, i.e. design by manufacturing simulation (DMS) and visual evaluation. As mentioned in section 1, DMS is an effective approach to mass producibility. A well-established product model and the related process model not only facilitate the capture and utilization of information generated during the design phase, but also perform as the analytical virtual prototype for engineering analysis based on computer simulation. Therefore, product development life cycle concerns, such as manufacturing, assembly, and production management, can be addressed at an early stage. On the other hand, the virtual prototype enables the visual presentation of the digital clay to potential customers by rendering the look and feel of the target product. This helps designers elaborate on designs based on the customer's perception and involvement, thus particularly useful for customized consumer products featuring aesthetic and ergonomics requirements. In such a way, a VP-based design environment (VPDE) enables the design, evaluation, and improvement of products by a CE team. In VPDE, the sequential development process is significantly improved by bridging different stages of product development via virtual prototypes, and enabling the customer-in-loop through applying VR techniques. Figure 3 illustrates a configuration of VPDE, which is composed of the following subsystems.

- *Visualization system*. Present 3D CAD systems have efficient modeling functions such as the parametric and feature-based functions. The problem of displaying CAD geometry in a VR environment relates to the large number of polygons in the complex geometry of a part. Typically, engineering workstations and PCs do not have graphic engines. Therefore it is computationally extensive to rotate 3D models, to shade models, to render images, and so on. Special VR hardware, for example, a Silicon Graphics workstation, is necessary for a

Figure 2
VP-aided design for customized products

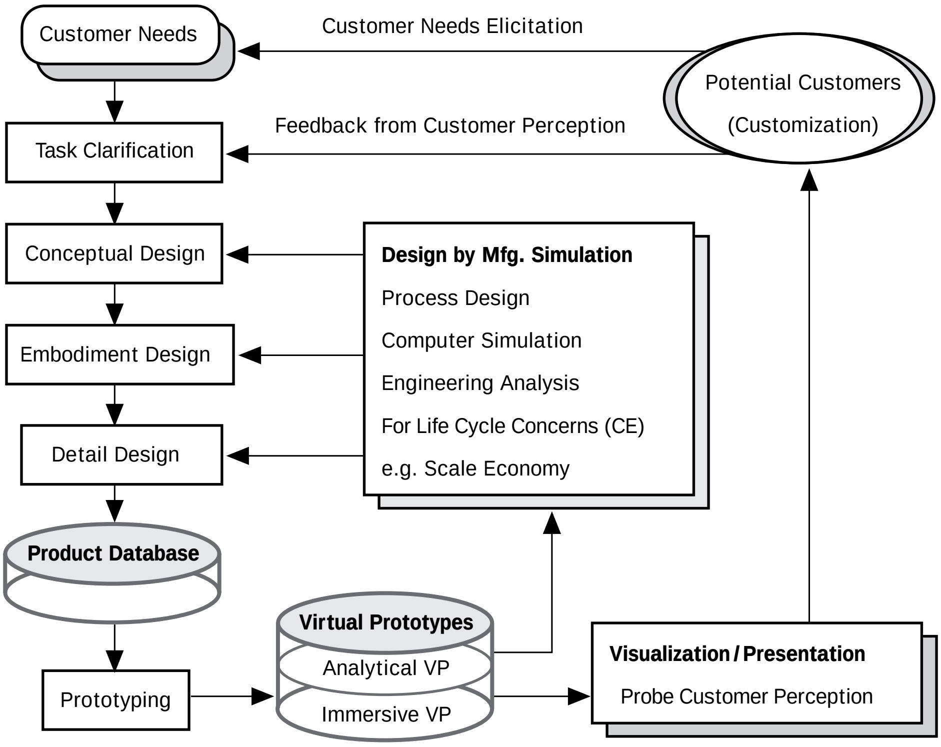
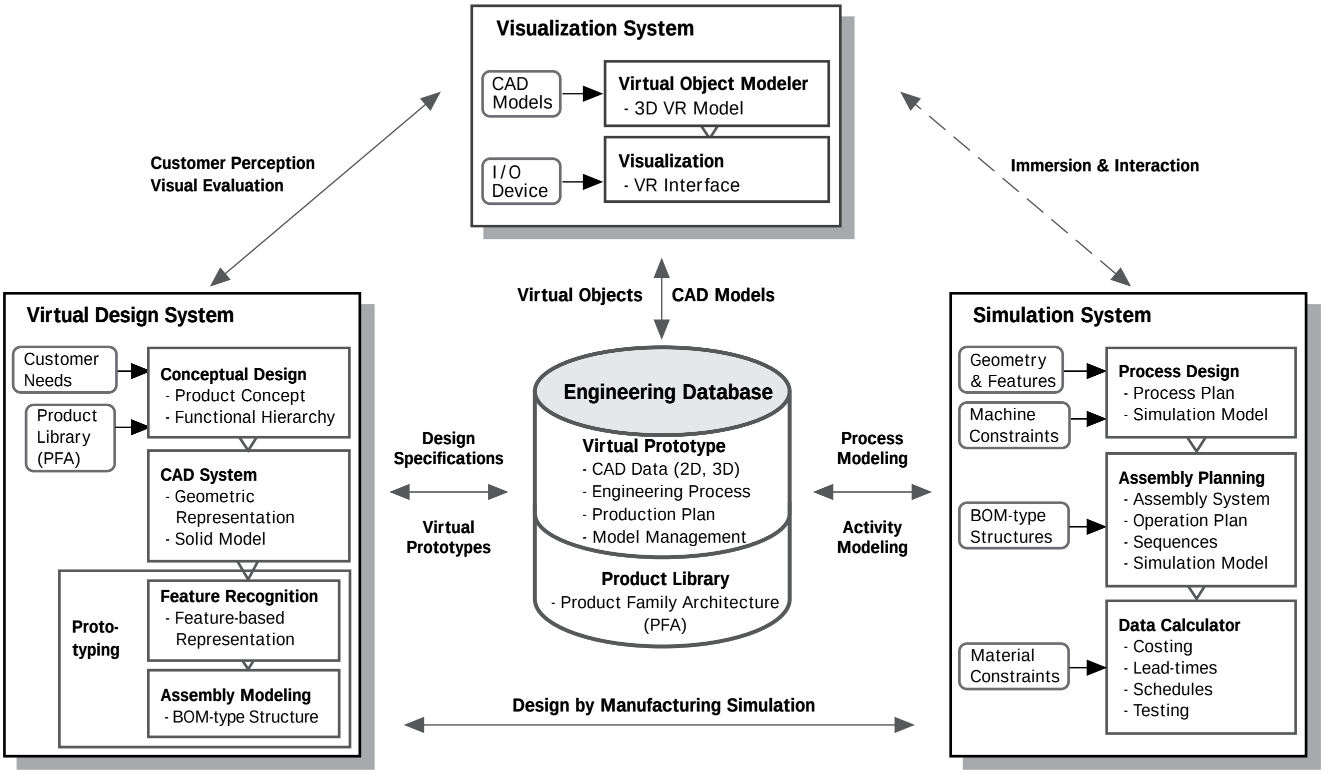


Figure 3
Configuration of VP-aided design environment (VPDE)



visualization system. Also important are algorithms to render these complex parts in a virtual world while maintaining a reasonable frame rate. As for difficulty in reading CAD-dependent data directly, it is feasible to exchange 3D CAD data to IGES (Initial Graphics Exchange Specifications) files. Then the system reads IGES files and creates the original 3D model. The visual presentation can probe the potential customer's perception on the target product being designed for design elaboration. Furthermore, it is possible to provide immersion in and interaction with the virtual world through real-time simulation.

- *Simulation system*. Both the product design and the choice of manufacturing processes affect the assessment of mass producibility required by mass customization. The underlying issue is the cost of manufacturing. The purpose of a simulation system is to integrate prototypes and manufacturing activities directly into design decision making by defining appropriate product, process and activity models. Thus, results from a simulation are fed directly into a product design decision. Given a virtual prototype, CAD models provide the basis for a process plan, which is necessary before simulation. The process plan is developed based on CAD models and machine constraints and performs as the basis for manufacturing simulation. The assembly line will be laid out in terms of stations and operations, either manual or automated, then the product will run down the line to simulate the process. The throughput, utilization, buffer sizes, and other simulation results can be determined. Virtual humans can be animated to simulate manual operators. In manufacturing simulation, each time a machine tool is actuated, the time and cost of that movement can be calculated from company standards. Similarly, the material is selected and indexed into the simulated machine so that the material costs and requirements can be calculated. Similar calculations can be performed for assembly simulation. In all these, partial cost, time and requirement data are assembled during the design process to give an indication of product cost and lead-time.
- *Virtual design system*. Design problem definitions and solutions will be developed in a virtual design system. That is, it should be possible to formulate and solve selection and compromise design specifications (DSPs) for product design. It is through these DSPs that information produced during prototyping, simulation, and evaluation is fed back to the designer to aid in decision making. For example, process plans and assembly plans are the contents of a DSP. Another important task of a virtual design system is the prototyping where virtual prototypes are interactively generated based on CAD models. In prototyping, the manufacturing process model, assembly model and scheduling model are prepared around the product data model. By prototyping, a virtual prototype is developed as an information model of a product with models of its manufacturing, assembly and production management ready to be manipulated by a designer via computer simulation to instantiate such manufacturing information.
- *Engineering database*. As the core of VPDE, the engineering database system (ENDB) mainly manages 3D CAD data and product library and has interfaces to other systems such as the master database and simulation systems. Traditional database systems store only 2D CAD data and their attributes. They are usually called drawing management systems. They are designed for efficient manufacturing processes. However, it is impossible to build virtual models by using 2D drawings. The requirements for ENDB involve: (1) management of current CAD data including part data and configuration tree, (2) maintenance of the product library with a product family architecture built-in, (3) management of the engineering process, e.g., work flow, (4) interfaces to other systems, such as CAD/CAM/CAE systems, and (5) information retrieval functions, such as parts, assembly and DSPs.

4. An implementation example

The design of a souvenir item (sundial) is selected as the test-bed in our preliminary implementation of VPDE. Figure 4 shows the current configuration. AutoCAD is used for preparing 2D drawings. DXF data format is used to build the interface from AutoCAD to the virtual design system. In the virtual design system, virtual objects are built for rendering and simulation. All components of products in the product library are pre-built by using the 3D Studio 4.0 and stored by a product family architecture (PFA). All these component models are then converted to WorldToolKit™ 2.1 SGI Onyx format (Neutral File Format æ NFF) through a built-in conversion utility for visualization. Attributes are attached to all parts and sub-assemblies to specify certain product characteristics such as physical properties (e.g. color and texture). Parts and sub-assemblies that contribute to distinct product types are identified so that this information can be later used for assembly plan generation. In the (VR) visualization system, the CrystalEyes™ glasses and emitter are employed to obtain stereoscopic visual effects. In addition to geometric representation, the underlying product model involving the visualization of prototypes relates to an appropriate PFA. PFA comprises a product library with various types of components and configuration trees for synthesizing end products. In such a way, product customization (variety) can be captured and dealt with by the PFA. Figure 5 illustrates the PFA for the souvenir example, which manifests diverse configurations of different customized sundials. The aesthetic visualization of the digital clay helps to explore the customer's perception on the target product, as shown in Figure 6.

An external simulation tool, ProModel™ (1997), is adopted in the manufacturing simulation system. Using ProModel, objects ranging from individual products to complex factory scenarios can be modeled with functional properties and motion data. Process plans are developed according to CAD drawings and machine constraints. In the souvenir example, a CNC milling machine is selected as the main machine tool. The rational consideration is that customized products are often characterized by large varieties with a small lot size, which requires flexible manufacturing facilities. For each component of the souvenir, CNC programs are generated from CAD drawings using software

Figure 4
An implementation example of VPDE

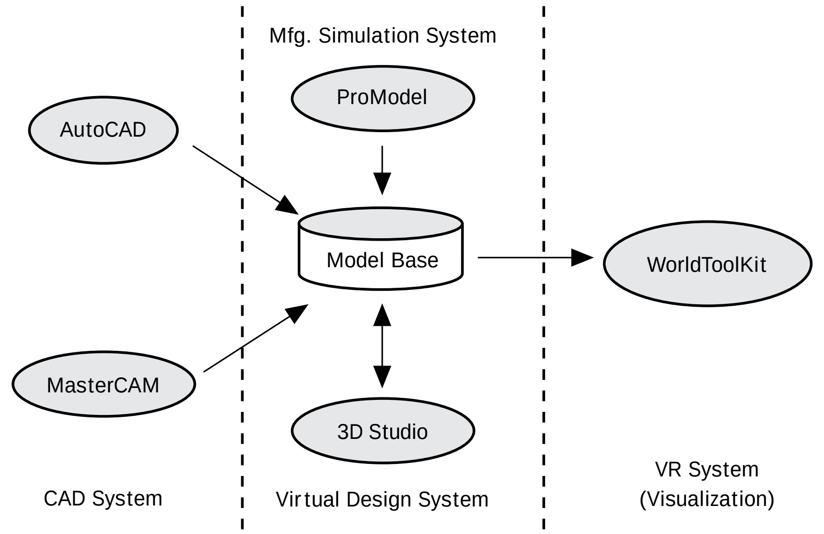
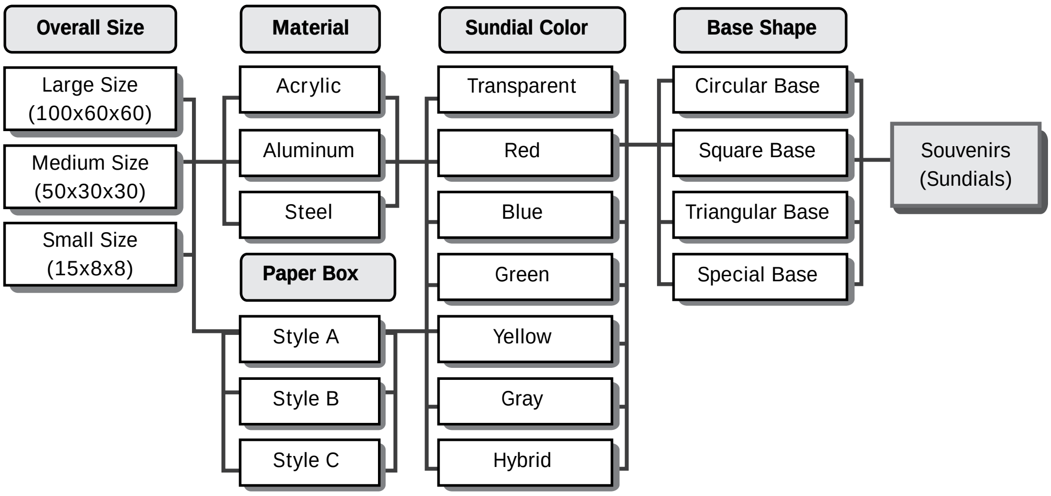


Figure 6
Visual presentation of a virtual prototype

Figure 5
The PFA for various customized souvenirs



MasterCAM, from which each machining process can be simulated to estimate the machining time and costs. Figure 7 illustrates a virtual modeling of the CNC milling machine. Small details such as screws, textural surfaces and decals are left out in machine modeling since they are unnecessary to the function, performance, or realism of the machine model.

During the design stage, the customer selects desirable product features from the PFA of the sundial. The virtual prototype of sundial will then be automatically generated in a VR environment (WorldToolKit) by extracting pre-built component models from the PFA (see Figure 6). The immersive design detailer (IDD) employs VR technology to immerse the customer in the virtual environment for detailed product visualization and modifications. The customer's body motion information such as 3D translation and orientation of the head, limbs, hand and torso is tracked by sensors attached to a head-mounted display (HMD) and datagloves so that the virtual prototype can be immersively evaluated and modified.

After iterative evaluation and modifications of the virtual prototype, the appropriate assembly operations and sequences can be generated by recording user-performed assembly operations. Figure 8 illustrates the use of the input devices (datagloves) to manipulate parts so as to imitate manual assembly operations and generate the assembly plan. Subsequently, the assembly line for the execution of the generated assembly plan can be configured in terms of stations, operations and tools according to the product model supported around a bill-of-material (BOM) type structure (Figure 9). Figure 10 gives the configuration of a manual assembly system configured in a virtual environment for the souvenir's assembly. The performance of different assembly plans is evaluated using ProModel simulation in conjunction with the virtual assembly model. Figure 11 gives an example of assembly planning simulation in ProModel, in which the statistics suggest scheme 2 as the optimal one.

Figure 7
Virtual modelling of a CNC milling machine, work-piece and control panel

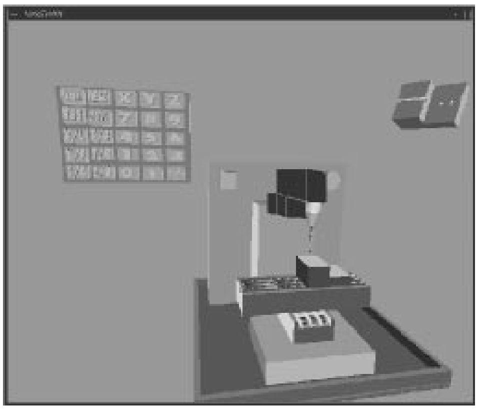


Figure 8
Virtual design and assembly of the souvenir (sundial)

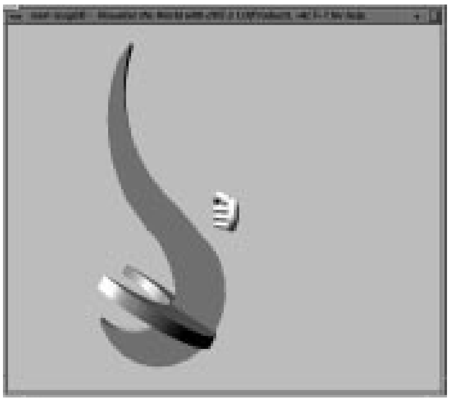
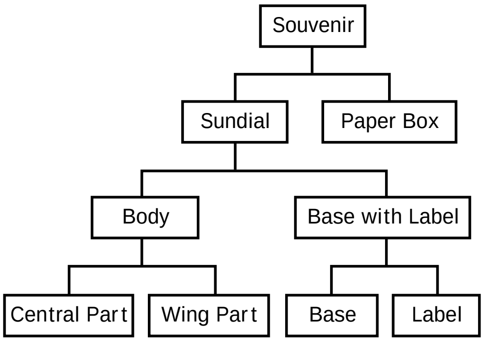


Figure 9
BOM-type product structure model for the sundial



According to the virtual prototype, the time and costs associated with machining and assembly can be statistically summarized based on simulation. By adding data on labor rate and overhead, the manufacturing and assembly costs can thus be estimated. According to the process and assembly planning coherent with the virtual prototype, the material cost and requirements can be calculated, along with tooling costs and requirements. Finally, the overall cost and lead-time are estimated and scheduled.

5. Concluding remarks

In this paper, we have presented the idea of combining virtual prototyping with design by manufacturing techniques for the development of a virtual prototyping-aided design environment. Our particular application is customized product development, which is facing the challenges of keeping mass producibility and exploring customer perception. By constructing virtual prototypes, accurate assessments of mass producibility and customer acceptance enable better design of customized products. We outlined the research issues associated with the development of such a environment including product representation and prototype generation, human-computer interaction, manufacturing process simulation, and product library maintenance.

Based on pilot implementation, we made these observations: (1) the combination of virtual prototyping and VR techniques has tremendous potential in providing advanced visualization and manipulation capabilities for customized product development by enabling visual evaluation and acquiring the customer's perception on the target product; (2) the development of a virtual prototyping-aided design environment shows great promise in providing intuitive guidelines for people engaged in design and (virtual) prototyping; (3) such an environment provides a unified framework for bridging different stages of product development by facilitating the capture and utilization of information generated during the design phase and the simultaneous generation, at design time, of manufacturing and production planning data; (4) product family architecture plays an important role in virtual prototyping-aided design of customized products by reusing previous designs and production plans, potentially maintaining the integrity of product family and the continuity of infrastructure, hence maintaining the economy of scale.

Figure 10
Assembly system design for souvenir assembly

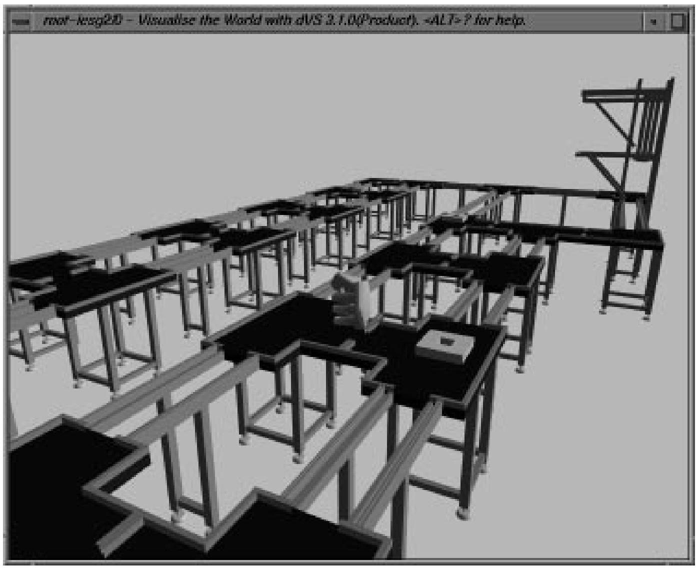
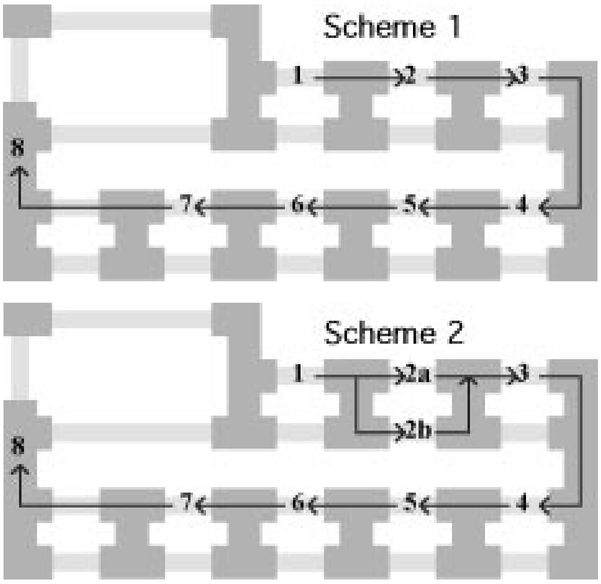


Figure 11
Simulation on assembly plans for manual assembly system



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