Journal of Computing and Information Science in Engineering

Technical Note

This section contains shorter technical papers. These shorter papers will be subjected to the same review process as that for full papers.

Definition and Review of Virtual Prototyping

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Virtual Prototyping (VP) technique has been interpreted in many different ways, which causes confusion and misunderstanding among researchers and practitioners. Based on a review of the current related research and application, this paper proposes a definition of VP as well as components of a virtual prototype. VP is then compared with and distinguished from virtual reality (VR), virtual environment (VE), and virtual manufacturing (VM) techniques. Given the proposed definition and review of VP, future VP related research topics are suggested. [DOI: 10.1115/1.1526508]

Keywords: Virtual Prototyping, Virtual Reality, Computer Simulation, Virtual Environment, Virtual Manufacturing

Introduction

Virtual prototyping (VP) technique has been studied and implemented in recent years in engineering design. Quite often this term was used and interpreted in many different ways, which has caused confusion and even misunderstanding among readers. When VP is mingled with Virtual Reality (VR) or Virtual Environment (VE), the extent of confusion increases. In addition, a variety of VP applications have been documented in literature. However, it is difficult to put these applications to an appropriate context and research framework, partially because of the different interpretation and levels of understanding of VP. It is thus felt by the author that a clarification of the VP definition will be helpful, based on which the future research directions on VP can be elaborated.

Various VP Definitions

Currently quite a number of VP definitions are given in literature and in industry. The following includes a few of these definitions.

"Virtual Prototyping (VP) is a relatively new technology which involves the use of Virtual Reality (VR) and other computer technologies to create digital prototypes."—Gowda et al. [1] from Michigan State University. This definition specifically stated that the use of VR is one of the characteristics of VP. Also this definition makes no distinction of a digital prototype and a virtual prototype.

"By virtual prototyping, we refer to the process of simulating the user, the product, and their combined (physical) interaction in software through the different stages of product design, and the quantitative performance analysis of the product."—Song et al. [2] from University of Pennsylvania. This definition emphasizes human-product interaction and the function of virtual prototyping in product design and analysis.

"In the mechanical engineering definition of virtual prototyping (VPME), the idea is to replace physical mock-ups by software prototypes. This includes also all kinds of geometrical and functional simulations, whether or not involving humans."—Antonino and Zachmann [3] from BMW. This work also quoted the definition of digital mock-up from ref. [4], which defined the Digital mock-up (DMU) as a realistic computer simulation of a product with the capability of all required functions from design/engineering, manufacturing, product service, up to maintenance and product recycling. The authors categorized virtual prototypes as a subset of digital mock-ups. Also the human-product interaction is not an essential component of VP by the definition.

"Virtual prototyping, namely digital mock-ups (DMU),..."—Fraunhofer Institute for Computer Graphics [5]. This definition states that VP is DMU.

There are other definitions published in literature and on the Internet. In summary, the difference of these definitions centers on following questions:

- Is a virtual prototype the same as a digital mock-up?
- What are the functions of VP?
- Should VP include a human-product interaction component?
- Does VP have to use VR techniques?
- Does VP have to include the optimization process?

This work will try to address these questions in the proposed definition of VP.

Proposed Definition

The Academic Press Dictionary of Science and Technology [6] defines that "*Prototype*: an early or original form;... (in *engineering*) a full-scale model of a structure or piece of equipment, used in evaluating form, design, fit, and performance." Also the "*Mock-up*: (in *engineering)* a scale model, often full-size, of a structure, apparatus, or vehicle; used for study, training, or testing and to determine if the apparatus can be manufactured easily and economically." In real work, "prototype" and "mock-up" are often used interchangeably, i.e., they all involve an either scale or full-scale model of a structure or apparatus used for testing and evaluation. Based on the same essence of the two concepts, this work makes no distinction between a prototype and a mock-up. Literally, therefore, "virtual" prototype should have the same meaning as the "digital" mock-up.

From the definition of prototype, one can summarize the characteristics of a prototype as below:

■ A model of a structure or apparatus (or a product)

Contributed by the Engineering Simulation and Visualization Committee for publication in the JOURNAL OF COMPUTING AND INFORMATION SCIENCE IN ENGINEERING. Manuscript received May 2001; revised October 2002. Associate Editor: S. Jayaram.

■ Used for testing and evaluating form, design fit, performance, and manufacturability.
■ Used for study and training.

In a conventional product development process, a prototype is usually constructed to prove design concepts, evaluate design alternatives, test product manufacturability, and often just to present a product [7]. With the goal of replacing physical prototype electronically, a virtual prototype must first serve the same functions and even more of a physical prototype, regardless of which techniques are used. In light of this, a virtual prototype should be able to be used to ‘‘test’’ a product’s form and performances, and be used for training and other studies. In addition, a physical prototype usually allows human beings’ sensory evaluation of a product, such as color, form, aesthetic features, feel, fitness, and so on. Product’s ergonomics is also of an increasing concern. To substitute these functions of a physical prototype, a human-product interaction component should be included in a virtual prototype.

From the definition point of view, it might be wise to not include specific realization techniques in the definition of a noun. In light of this, virtual reality techniques will not be explicitly stated in the proposed definition of virtual prototyping, even though VR techniques could play an important role in realizing VP, which will be discussed in later sections.

Does virtual prototyping have to include optimization in the definition? It is natural to extend virtual testing to design optimization, and product optimization is one of the main purposes of using prototypes. The argument is that a virtual prototype is not necessarily be used for design optimization; it might be used just for concept verification, presentation, and training. Secondly, design optimization based on virtual prototypes entails many new and challenging issues. Thus VP-based design optimization deserves to be an independent topic and such distinction will help to address research issues of different nature. This statement will be illustrated further in the Future Research of VP section.

Consequentially, the proposed virtual prototyping is defined as below:

“Virtual prototype, or digital mock-up, is a computer simulation of a physical product that can be presented, analyzed, and tested from concerned product life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping (VP).”

The proposed definition is not radically different from other definitions. However, the definition specifically states that a virtual prototype is a digital mock-up; describes the function of a virtual prototype; implies the importance of human-product interaction; excludes the virtual reality technique and design optimization from the definition; and differentiates the virtual prototype and virtual prototyping techniques. It is to be noted that the acronym VP stands for virtual prototyping and not for the virtual prototype.

Components of a Virtual Prototype

Based on the proposed definition of VP, an elaboration of virtual prototype components is attempted. First, a computer simulation of a product is required. At current stage, a 3D solid model is the widely accepted product presentation, usually parametric. Second, for a virtual prototype to be presented as a real physical model, a human-product interaction model is desired. Ideally, a virtual product can be viewed, listened, smelled, and touched by an engineer or a customer. This is the area that virtual reality techniques can play an important role. More importantly, various perspectives of the designed product should be able to be tested and evaluated. In summary, a complete virtual prototype should include essentially three types of models as follows (as shown in Fig. 1):

■ A 3D solid model,
■ A human-product interaction model, and
■ Perspective test related models.

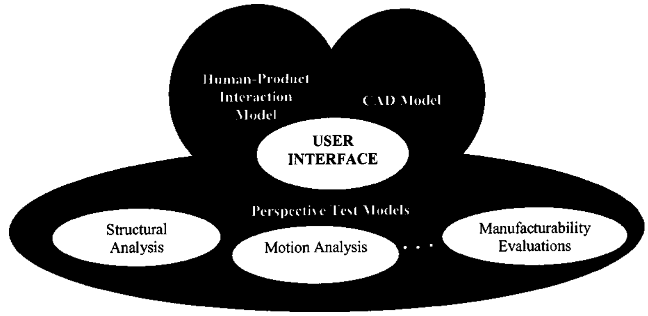

Fig. 1 Components of a Virtual Prototype.

From Fig. 1, one can see that various interrelated models are built to virtually present, analyze and test a product. The user interface serves as the integration component that coordinates the behavior of models and provides useful information to the system user. Depending on applications, a virtual prototype may only include a subset of these components.

Virtual Prototyping versus Virtual Reality/Environment

Virtual Reality (VR), as defined by the Academic Press Dictionary of Science and Technology [6], is a computer simulation of a system, either real or metaphorical, that allows a user to perform operations on a simulated system and shows the effects in real time; e.g., a system for architects might allow the user to ‘‘walk’’ through a proposed building design, displaying how the building would look to someone actually inside it. VR is rooted in the area of artificial intelligence and computer engineering. In the design and manufacturing field, virtual environment (VE) is often used as a thesaurus of VR [8–10]). VE is sometimes referred as virtual reality environment. Ellis [11] defines a VE as the synthetic, interactive, illusory environment perceived when a user wears or inhabits appropriate apparatus, providing a coordinated presentation of sensory information mimicking that of a physical environment. The above definitions of VR and VE are essentially identical. In this paper we do not distinguish VR, VE, and virtual reality environment. Only VE, as defined by Ellis, will be used in later sections as a representative of all the three concepts.

Gupta [12] stated that in VE the user becomes *immersed* and experiences a strong sense of presence; the *immersion* is the striking characteristic of VE. Then, what is the difference between VP and VE? Though VP and VE are easily mixed up, their definitions are significantly different. First, Virtual prototyping (VP) is the construction and testing process of a virtual prototype; while a VE is an environment. Second, a VP system does not necessarily incorporate a virtual environment, i.e., the *immersion* is not absolutely required. Krovi et al. [13] and Song et al. [2] presented a design example using virtual prototyping. They integrated a parametric CAD model, a human-product interaction model, kinematic and dynamic model, and mechanism design model to study a virtual product for people with disabilities. In this design project, no immersive virtual reality techniques have been used. Mase et al. [14] used finite element analysis with the assistance of a knowledge system for a full bumper testing and design study. The University of Iowa has been developing a virtual proving ground for vehicle designs [15–17]. Rai et al. [18] from Xerox Corp. applies VP in their Xerographic charging component design. In this project, a CAD modeler, finite element information, and functional analysis models were well integrated for design evaluation and optimization without physical prototypes.

Given the difference between the two, VE, however, can greatly enhance VP in many areas,

1 VE facilitates an immersive understanding of a virtual product, especially for ergonomic and aesthetic design, as well as customer participation in design and evaluation. VE can give the

designers and customers a strong visual, aural, and tactile sense of a virtual product. The ergonomic and aesthetic features of a product can be evaluated by incorporating the user in the virtual environment. Such an environment can thus help to design extremely customized product [19]. Jayaram et al. [20,21] presented an integrated VP system that humans can evaluate automotive interiors and make design changes in a virtual environment. The Iowa State University used a VE interface for the visualization of Computer Fluid Dynamics (CFD) data [22].

2 VE assists intuitive surface modeling and sculpture body modeling. A new modeling technique is attracting more and more interests, i.e., the integration of VE and conventional CAD technique. Current commercial CAD packages are excellent in simple geometry modeling; but the surface and sculpture body modeling is rather clumsy and counter-intuitive. By incorporating the designer in a VE, the modeling data can be changed in real-time and be fed back in the CAD system for geometric modeling. Researchers at the Washington State University have been working in this area. An example is the swept volume generation for assembly [23]. They use a VE interface to help modeling the trajectory of assembly and then create swept volume geometry in a CAD system. Furlong [24] investigated the use of free-form deformation to create virtual sculptures. Furlong et al. [25,26] and Evans et al. [27] applied VE in the mechanism design. Yeh and Vance [28] presented a technique that a human can manipulate a NURBS curve to change the geometry; the change of geometry was reflected in a finite element analysis (FEA) model; the sensitivity of the geometry change was then fed back for design improvement. Researchers at the University of Wisconsin-Madison aim at developing a VR (voice and hand input-based interface) assisted CAD tool, called COVIRDS-COnceptual VIRtual Design System [29–31]. A detailed review in this area is in ref. [32].

3 VE enhances the interface of finite element analysis. An interesting project is carried on by Haase and Preß [33]. They designed and implemented an immersive finite element pre- and postprocessor that incorporates a powerful virtual environment. A designer can ‘‘grasp’’ and move a node in the mesh definition and thus making the mesh generation more controllable and intuitive.

4 VE helps in assembly, manufacturability and maintainability analysis. It is difficult to quantify the ease of assembly, the extent of manufacturability and maintainability using conventional means. VE provides a possibility to immerse an operator in the virtual environment, performing the specific assembly, manufacturing, or maintenance task. Provided the feedback information is accurate enough, these hard-to-quantify aspects can be accurately compared. The System Realization Laboratory at the Georgia Institute of Technology has been working on virtual prototyping systems for assembly, disassembly, and service [34–36]. Lee and Hahn [37,38] worked on a specification of virtual manufacturing processes. Antonishek et al. [39] describes an environment in which a developer uses VR tools to intuitively interact with and verify complex product assemblies. Other works are included in refs [40–42].

The application of VE in manufacturability study leads to another concept–virtual manufacturing (VM).

Virtual Prototyping versus Virtual Manufacturing

Virtual Manufacturing (VM), as defined in ref. [43], is the use of computer models and simulations of manufacturing processes to aid in the design and production of manufactured products. Lawrence Associates Inc. [43] defines ‘‘Virtual Manufacturing (VM) is an integrated, synthetic manufacturing environment exercised to enhance all levels of decision and control.’’ Three paradigms of VM have also been proposed in this report, including *design-centered VM, production-centered VM, and control-centered VM*.

Literally from these definitions, *the design-centered VM* has a similar content as the VP from assembly and manufacturing aspects alone. If looked at a broader scope, however, all the three paradigms serve as the basis for manufacturability analysis in VP. A product's manufacturability primarily relates to the feasibility and the extent of ease of fabrication. A natural index to describe the extent of fabrication ease is the associated manufacturing cost. The manufacturing cost is influenced by the process planning, operation parameter specification, production planning and control, logistics, and so on. Thus to accurately quantify a virtual product's manufacturability, supporting data from the entire production process is required. Consequently, to support an accurate manufacturability analysis in virtual prototyping, VM is the fundamental and indispensable technique [44–46].

Also it is worth noting that the VE technique is not specifically stated in the definition of VM. This implies that VM can be simulated in other ways without a VE. However, as illustrated before in this paper, a VE can help describe the production process and control.

Virtual Prototyping versus Conventional Engineering Simulation

While talking about virtual prototyping, a commonly asked question is ‘‘What is different in VP versus the conventional simulation?’’ As the definition states, virtual prototyping is essentially a simulation process. If the conventional simulation is understood as only to gain the understanding of a particular product aspect [47], then VP will have a bigger scope as it attempts to address all of the related product aspects in order to substitute physical prototypes. Consequently, VP becomes a more technically demanding task than an individual simulation. In addition, VP emphasizes more on the human-production interaction as compared with conventional simulation. Nevertheless, VP is essentially a simulation process as stated in the proposed VP definition. Trying to identify the difference between these two concepts might be difficult and unnecessary.

Future Research of VP

With the goal of replacing physical prototypes, VP has a great potential to improve the current product development process. Possible future research or development directions are suggested below, in a hope to stimulate more interests and discussions in this area:

1 Integration of design, analysis, and simulation tools.

One of the limitations of today's VP technique is the lack of a seamless method for data exchange between various tools. Product data presentation and database research will still be a major topic. New methods that facilitate tool integration need to be developed.

2 VP for manufacturability, maintainability, serviceability analysis.

Since product manufacturability, maintainability, and serviceability are not well understood, how to test these product aspects is still a question to be answered. The use of VP technology provides a promising path. For instance, a product's serviceability could be quantified by incorporating a service technician to perform the service task in a virtual environment. Then the serviceability of different design alternatives could be compared. Specific research topics could include the rapid generation of a virtual environment using the 3-D solid product data, methods of evaluating various product aspects, calibration of virtual prototyping processes, and the error analysis of virtual prototyping against the physical prototyping.

3 Fault-tolerance of VP Systems

Current virtual prototyping methods and tools bear fundamental errors when compared with physical prototyping. The errors could be due to the computation time delay, image processing time delay, and the uneasiness of the user in a virtual environment. Product data may also deteriorate or corrupt during exchange in various platforms. Thus a fault-tolerant VP system is to be studied to ensure that VP gives trust-worthy engineering testing data and any possible error should be quantified.

4 VP-based Design Optimization

If various product aspects can be adequately described by virtual prototypes, a quantitative design optimum can possibly be obtained. However VP-based design optimization presents new challenges to conventional optimization. First, the VP-based optimization has to be very efficient in identifying the optimum since the VP is mostly computation-intensive at present and in the foreseeable future. Second, VP-based design optimization usually involves multiple design goals from different disciplines and therefore it can be formulated as a multidisciplinary optimization problem. Thirdly the VP-based design optimization has to take into consideration of the possible virtual prototyping errors, i.e., the obtained optimum has to be robust to intrinsic model inaccuracies and computation errors. Current simulation-based design optimization and multidisciplinary optimization methods might be borrowed to facilitate the VP-based design optimization.

5 VP-centered Concurrent Design Environment

Concurrent design is done presently through teamwork in industry. This manner often causes information chaos, duplicated effort, and management difficulties [48]. In addition, the design optimum cannot be quantitatively obtained. VP provides a means to quantitatively describe product behavior from various aspects and thus could possibly be used as a fundamental tool to support a quantitative concurrent design.

Acknowledgment

The financial support from the Natural Sciences and Engineering Research Council (NSERC) of Canada is gratefully acknowledged.

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