Int J Adv Manuf Technol (2007) 31: 846–856
DOI 10.1007/s00170-005-0267-7

ORIGINAL ARTICLE

J. Cecil · A. Kanchanapiboon

Virtual engineering approaches in product and process design

Received: 18 March 2005 / Accepted: 11 May 2005 / Published online: 8 June 2006

Abstract Virtual prototyping techniques are being extensively used in industry world wide, as they provide cross-functional evaluation at a lower cost, enable engineers to consider downstream issues earlier in the product design cycle, as well as facilitate better communication of product/process design issues among engineers of varying backgrounds. This paper provides a comprehensive literature review on virtual prototyping research efforts in various engineering domains, including design and manufacturing.

Keywords Virtual prototyping · Virtual manufacturing · Virtual reality

1 Introduction

The term "virtual prototype" (VP) has been widely used by various researchers and engineers. It is important to formally describe what constitutes a VP and, subsequently, provide a background on various types of virtual prototyping. In general, a VP is a 3-dimensional virtual reality (VR) based model which seeks to "mimic" a target (or "real-world") object, system, or environment. This model can be an object, system (or collection of objects), or a complex environment. The process of creating and using a VP in various applications can be referred to as virtual prototyping.

A VP, has certain characteristics which differentiates it from other models or prototypes. These include:

1. Appearance characteristics: VPs must possess accurate geometry, topology, and appearance, reflecting characteristics of the target part, object, system, or environment
2. Simulation characteristics: VPs should be capable of simulating engineering or science-based characteristics, including behavior with real-time responses
3. Representation criteria: A VP is a digital or computer-based representation
4. Interface criteria: VPs must possess the ability to interface VR technology and graphics, including supporting semi-immersive or immersive applications

Alternatively, a VP can be delineated as an engineering or science based VR model which can "mimic" or simulate a target system's (or object's) behavior, response, appearance, and geometry with a degree of realism comparable to the actual system or object. A brief note on the differences between VPs and computer-aided design/manufacturing (CAD/CAM) models is necessary, as these terms have been often been used incorrectly in engineering and general literature. In this paper, the term "virtual prototyping" is used in a formal context. A "virtual prototype" does not merely refer to computer models or representations for engineering applications. VPs possess major distinguishing characteristics listed earlier: a key characteristic is that they use VR technology and allow immersive or semi-immersive interaction. A true VP will support the use of VR technology and allow users to "immerse" themselves (they can essentially "enter" an environment and perform interactive tasks), walk around virtually, and allow a user to perform a variety of tasks, such as picking up a tool, turning a machine "on," unclamping/clamping a fixture, among other actions. Commercial software tools, such as Virtual NC® (whose use is described in the following sections), Envision®, and Vislab®, as well as numerous research environments and tools, such as VSAT [11] and PANDYA, fall into this category. With the help of adequate haptic interfaces, VPs can also provide force feedback to the user, depending on the type of physical activity involved.

Virtual prototyping techniques, in general, involves the use of VPs to propose, evaluate, refine, and compare potential solutions and identify problems. Another description of virtual prototyping is that it can be viewed as a modeling approach which seeks to simulate the functional

J. Cecil (✉) · A. Kanchanapiboon
Virtual Enterprise Engineering Laboratory (VEEL),
Center for Information-Based Manufacturing,
Department of Industrial Engineering,
New Mexico State University,
Las Cruces, NM 88003, USA
e-mail: jcecil@nmsu.edu

realism of a target system using VPs. Research findings have reiterated the fact that virtual prototyping also facilitates concurrent engineering (CE) by supporting the communication of ideas and earlier identification of problems and solutions among cross-functional team members in an organization.

Virtual Reality (VR) can be described as a technology which supports the creation of a computer-based environment for displaying 3-D immersive images, providing real-time user tracking system, facilitating human–computer interaction, and providing means for representing users in the environment. A VR environment (or simply, a virtual environment) supports immersive applications, such as walk-through (fly-through of proposed layouts, etc.), visualization of projected results (assembly/disassembly, collision detection, motion planning, etc.), object manipulation (load/unload, pick n place, etc.), and some forms of feedback mechanism (haptic interfaces, etc.).

The primary benefits of using a virtual prototyping approach include reducing the need to build physical prototypes, better communication among cross-functional product/process teams, earlier identification of downstream problems, and reduced product development cost. Using a VP, concurrent engineering teams (working on a new product idea) can propose designs, study them from different life cycle perspectives (such as function, manufacturability, testing, etc.), and then modify them early in the design cycle.

Researchers have also referred to VPs as "digital mock-ups." The process of creating a VP can be described as "virtual prototyping." VR technology usually refers to the hardware, software, and the related peripherals needed to create a virtual environment, such as sensors, motion trackers, 3-D eye wear, etc. This comprehensive review of research efforts has been categorized in this paper as follows (Table 1):

1. Virtual product design
2. Manufacturing
3. Related technologies

Table 1 Major categories in virtual prototyping addressed in this paper

Category	Applications
Virtual product design	Product design, such as the design of ships, automobiles, etc.
Manufacturing: - Factory-level simulation - Virtual prototyping of assembly processes - Virtual prototyping of lower level machining processes	Process design tasks, such as factory-level layout analysis, assembly analysis, simulation of metal cutting processes, etc.
Related technologies	Virtual reality technology, including advanced immersion systems, sensors, and haptic-based devices

Manufacturing can be decomposed into three sub-areas as follows: (1) factory-level prototyping; (2) virtual assembly environments; (3) virtual prototyping of lower level activities, such as machining.

2 Virtual manufacturing

The term "virtual manufacturing" has been used in a variety of contexts by numerous researchers. However, in a process design or manufacturing context, researchers and industry practitioners have never directly addressed the various sub-categories and levels of abstraction explicitly; this has led to confusion and misuse of what really constitutes a "virtual manufacturing" model, as well as contributed to the lack of clarity involving discussions on the creation of VPs in various categories (of manufacturing) and at varying levels of modeling abstractions. This section addresses these issues and defines the basic concepts of relevance.

The use of VPs in manufacturing can be grouped under virtual manufacturing and virtual assembly. A virtual manufacturing model is different from a virtual assembly model. The term "virtual manufacturing" involves the use of virtual prototyping techniques to aid in manufacturing process design issues for primarily metal-cutting applications. The term "virtual assembly" can be used to describe the use of VPs for assembly-oriented analysis and application.

The term "simulation" has been used (in the literature) to describe discrete event simulation (DES) approaches, which are quite different from virtual prototyping approaches. It is important to be aware that a manufacturing simulation model need not necessarily be a VP. However, depending on its characteristics, a simulation model may be described as a VP (the criteria which needs to be satisfied was summarized earlier in Sect. 1). Another important issue which needs to be clarified is the level of abstraction involved; in manufacturing, a VP can be built at three levels. These include the creation of VPs at the factory level, VPs addressing work-cell-level manufacturing process design (such as robotic work cells, etc.), and VPs simulating lower level processes and activities, such as metal removal, etc., at the machine or work station level. When a DES model satisfies the criteria to be referred as a VP (including use of VR technology and immersive interaction through sensors, etc.), it falls under the category of factory-level VPs.

Factory-level VPs are useful in designing plant layouts, comparing the efficiency of alternative process flows through a shop floor, and determining the impact of modifying shop floor components, etc. Mid-level manufacturing VPs are useful in exploring process design issues within a work cell, which may be composed of robots, human operators, material handling devices, conveyors, and machines; the interactions of these various components can be studied virtually. The process alternatives can be compared and modified as well. The lower level VPs focus on the simulation of metal cutting processes, including addressing process design issues, such as the study of machining tool path alternatives, design of fixtures, and other tools and their validation. In the following sections, research efforts addressing the design and use of VPs in manufacturing are discussed.

2.1 Factory-level virtual prototyping

The use of VP techniques to modify or simulate an existing shop floor, as well as help design a new layout using advanced methods (based on cellular manufacturing techniques), is delineated in Kesavadas and Ernzer [24]; the virtual shop floor system is called VRFact, and allows users to accomplish layout tasks in a virtual manner. Cellular manufacturing, in general, seeks to facilitate the design of a manufacturing shop floor using group technology (GT) concepts. The fundamental theme is to identify groups of part designs which can be manufactured using a common set of machines, termed as "cells." A well laid out manufacturing shop floor will help reduce idle time (include transport time between machines), reduce bottlenecks, and improve parts flow through a given shop floor or factory. Figure 1 provides a view of the VRFact environment for a sample shop floor.

DES models have been used for decades to identify machine tool usage and potential production bottlenecks, as well as to study material handling issues. In Kelsick et al. [23], an innovative approach is outlined where a DES environment is interfaced with a virtual cell layout environment; the DES tool is SLAM II® and the virtual cell environment is referred to as C2. C2 is a CAVE type of environment (an approximately 12’×12’×9’ room with projection screens on the walls and floor) and supports the use of peripherals, such as stereovision eyewear, motion trackers, and haptic sensors. The associated CAD models for use in the virtual environment are built using a variety of CAD tools, such as ProE®, World Up®, and MultiGen II®. The motion trackers are from Ascension Technologies (and are referred to as Flock of Birds®), the haptic sensors are from the Fakespace Corporation, and the eyewear is from CrystalEyes.

The development of advanced interactive devices and immersive displays has facilitated the understanding of the usefulness of VPs and VR in manufacturing. In Smith and Heim [36], the following topics are discussed: (1) production planning and shop floor analysis; (2) design review for the development of new products; and (3) the evaluation of real-time activities. The authors observe that, in the context of global competition and the market-driven need to produce innovative and low-cost products, manufacturing has become a decisive activity in the entire life cycle of the product. The crucial role of VR in manufacturing (especially before physical implementation) is highlighted as it pertains to the definition, modeling, and validation of manufacturing activities. An overview of VPs in various manufacturing domains is provided, including tool path control, assembly, lower level robotics program design, and plant floor control.

Quest® from Delmia Corporation is a DES tool with a VR interface, which are useful in creating new shop floors or modify existing ones. Users can bring in detailed CAD models of target machines, conveyors, automated transport mechanisms, etc., to enrich the factory environment.

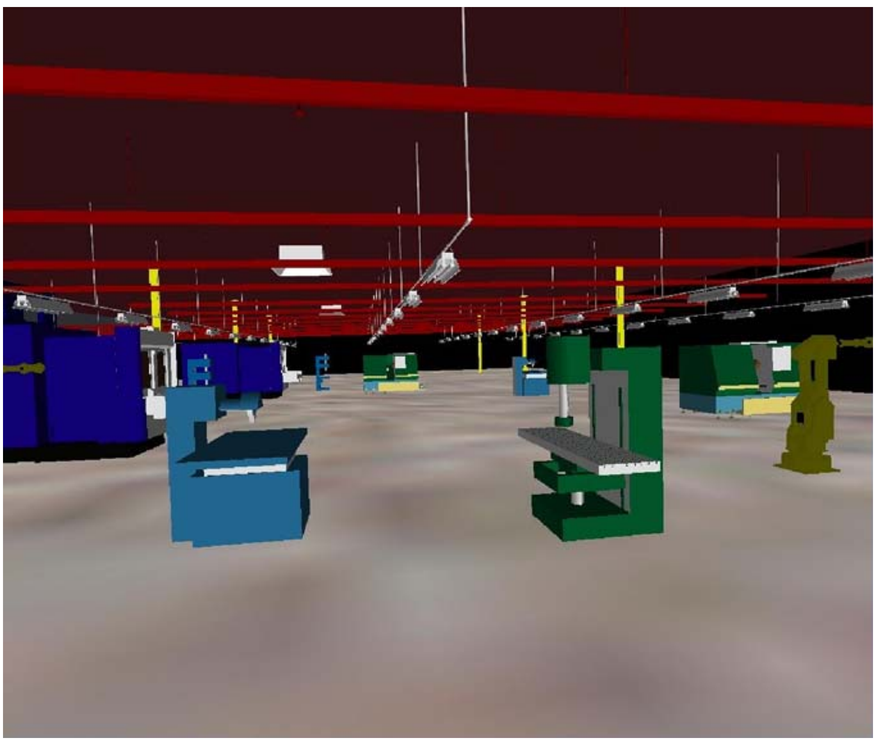


Fig. 1 A view of the VRFact virtual environment

2.2 Virtual prototyping of assembly tasks

Siddique and Rosen [35] described the application of virtual prototyping in product disassembly. VPs that can be used for designing a product and also disassembling it, as in cases of large machines, which have to be manufactured and then disassembled, transported and assembled again. The disassembly process can be performed by automated techniques or through interaction with the user. In Sharma et al. [34], the development of an augmented reality system called AREAS to support the analysis of assembly alternatives is elaborated. AREAS is an acronym for Augmented Reality system for Evaluating Assembly Sequences. Augmented-reality-based prototyping enables a user to see the real world and virtual world simultaneously. By comparing the virtual approaches and studying the problems experienced during physical assembly, certain constraints and problems can be identified early in design cycle.

One of the benchmark virtual assembly environments is VADE (see Fig. 2), which was developed at Washington State University (VADE continues to be refined and extended [21, 22]). It is one of the most advanced virtual assembly systems, which seeks to support product and process engineers working in a collaborative product development environment. VADE is an acronym for Virtual Assembly Design Environment. VADE provides comprehensive product realization support at various stages from the validation/verification of assembly plans to maintenance verification, as well as the generation of alternative plan generation in a post-production evaluation context. There are eight modules in VADE, each focusing on an important area of functionality; these include: collision detection, managing user interaction, inputs/outputs, design, dynamic handling and swept management. Apart from robust collision detection, VADE allows users to accomplish swept volume creation, as well as to perform parametric design modifications immersively.

Cecil et al. [8] outlined a virtual prototyping system called VSAT (Virtual environment for the assembly of SATellites) for evaluating satellite assemblies (see Fig. 3). The core modules of VAST includes a user interface module, task manager, assembly and assembly planner. The assembly planner has two options: (1) manual input of assembly plans using VR interface; (2) automated generation of assembly sequences. Assembly plans were generated automatically based on precedence constraints and optimization criteria. Other modules include a part/device interaction manager, which allows the user to pick up satellite pieces and assemble them manually, as well as to perform "what if" analysis relating to the comparison of assembly alternatives. The primary purpose of this immersive virtual environment is to assist engineers in evaluating the assembly and process feasibility of candidate satellite designs.

Bodner et al. [7] presented a virtual prototyping system for simulating the assembly of printed circuit boards

Fig. 2 Images of the VADE virtual assembly environment

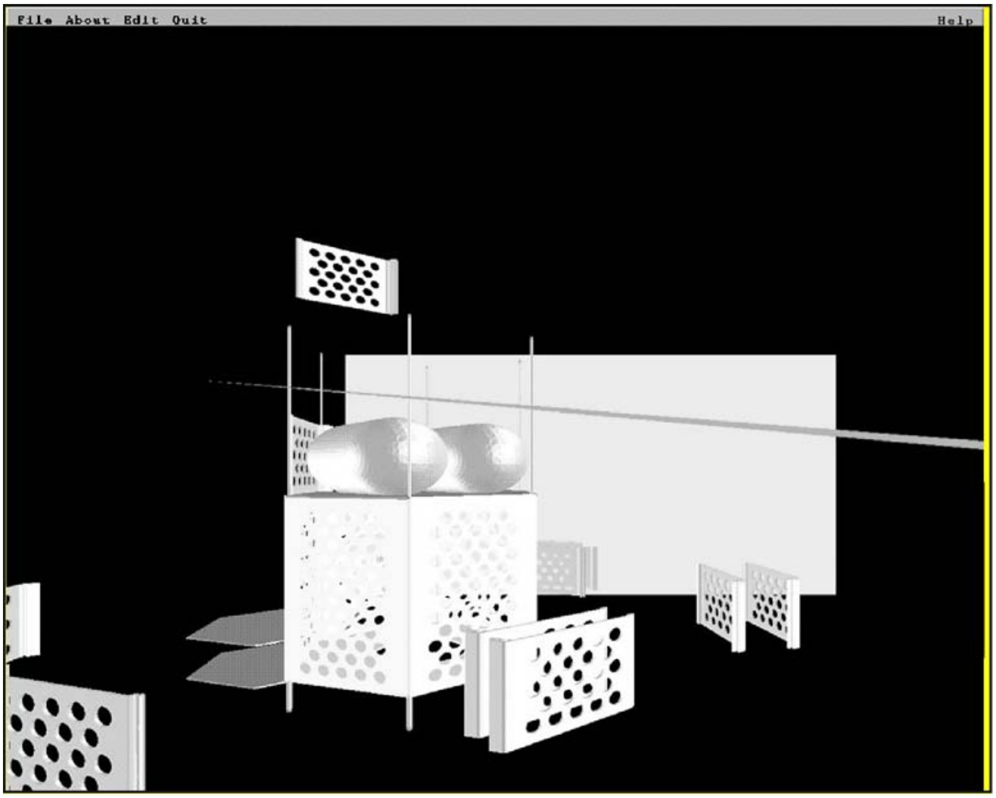


Fig. 3 VSAT: a virtual environment for satellite assembly analysis

(PCB). In the assembly approach modeled, the machine frames are stationary, while the placement mechanism moves to accomplish the assembly task. The virtual prototyping environment helped operators to determine placement and feeder assignments. The 3-D animation models were created using Virtual NC (from Delmia) for

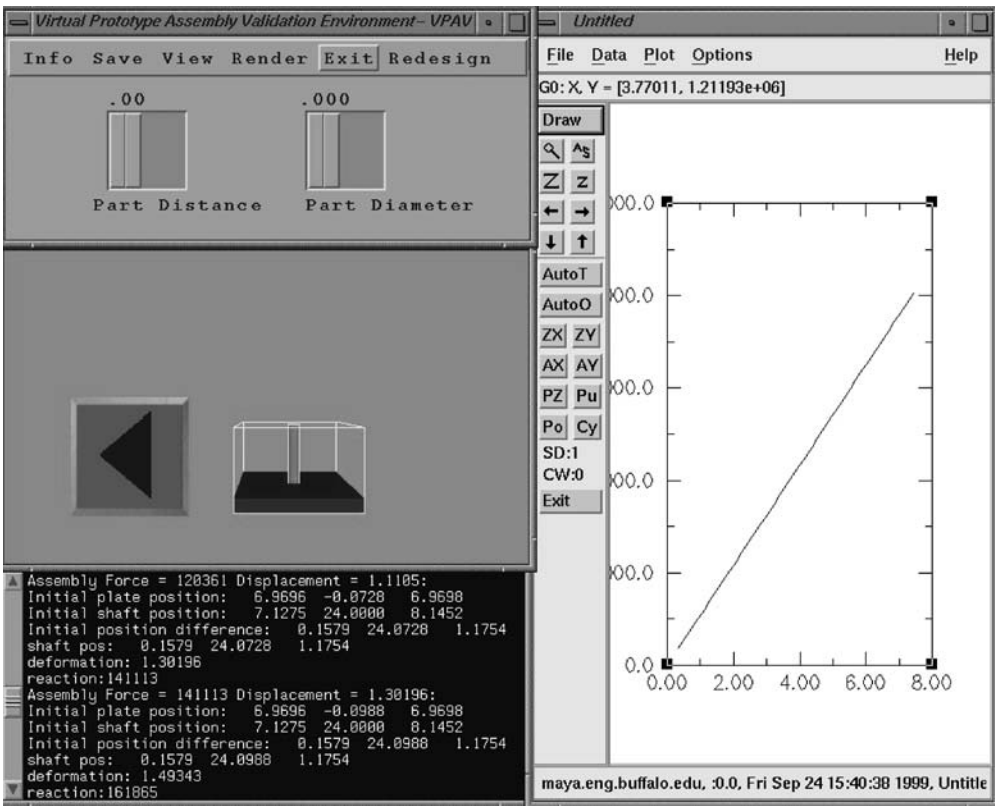


Fig. 4 A view of the VPAVE environment

model validation and machine operation understanding. However, in the implemented approach, immersive VR motion trackers and sensors were not used.

Deviprasad and Kesavadas [16] discussed VPAVE, in which virtual prototyping is used to validate assembly components using finite element simulation (Fig. 4 provides a view of this VR environment). Chryssolouris et al. [12] discussed the use of VR-based methods for the verification of performance factors in manual assembly processes. Mok et al. [30] integrated the virtual manufacturing system with a CAD/CAM design environment to calculate the cost for the assembly and disassembly of a part. Virtual manufacturing concepts are used in cell measuring applications as well.

Mikchevitch et al. [29] discussed the aspects of fast and realistic simulation of flexible parts during the assembly/disassembly process. Initially, a study of current assembly/disassembly processes is performed; a new system integrating real-time and interactive mechanical models is proposed, and, finally, an example of the interactive mechanical model for the virtual assembly/disassembly of flexible beam parts is presented. The approach is then subjected to evaluations by performing numerical tests.

2.3 Virtual prototyping of lower level machining activities

While there are numerous CAD/CAM software tools widely used in industry today for lower level manufacturing process simulation, only a few of them can be described as belonging to the category of VR-based prototyping (or virtual prototyping). For example, tools such as Master CAM® and CAM Works® can allow users to "visualize" machining or metal cutting activities (such tool paths in G-code and other formats). However, they do not allow a user to wear VR sensors, motion trackers, or stereovision eyewear as part of immersive activities.

Several commercial tools are available for virtual process design. Virtual NC® (from Delmia) can be used to create VR-based models of machining work cells, including target work pieces, metal cutting tools, and computer numerical control machines. Validation and analysis of work cell layouts and tool paths (specified in G-codes) can be performed virtually (Fig. 5 shows a view of a milling machine created using Virtual NC®). Jack® is a software package (from EDS) which enables users to address ergonomics-related issues. This tool is useful especially for identifying problems which can cause physical strain on human workers involved in assembly and other manufacturing tasks. Both of these tools allow interfacing to VR peripherals, such as motion trackers and interactive wands that support immersive capabilities.

Shao et al. [33] explained the modeling of a virtual grinding machine by using Open GL tools and Virtual Reality Modeling Language (VRML). A shared virtual prototyping environment is described by Jasnoch et al. [19] to reduce manufacturing cost and time. The major domains of application which are managed as scene graph divisions include simulation analysis, product design, process design, and the virtual environment (VR-oriented), which communicate by exchanging messages with each other.

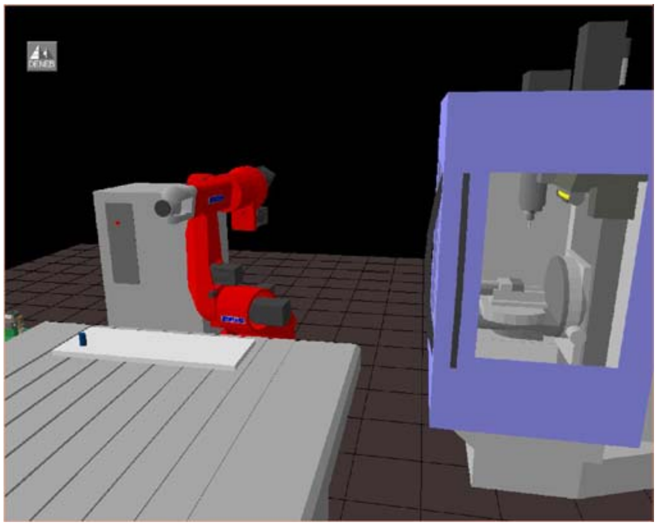


Fig. 5 View of a virtual milling machine in Delmia's Virtual NC software environment

Peng and Loftus [31] outlined an approach to support an integrated computer-aided process planning (CAPP)/VR system; a method is described to quickly model the 3D information from a target process environment and to map a program structure to achieve improved sharing of associated VR resources. Using the proposed architecture, which involves the use of a VR design interface, the integrated system can respond to dynamic manufacturing processes. Examples from metal cutting applications are used to validate the proposed integrated approach. Chung and Peng [13] delineated a web-based VR CAPP system to generate process plans, as well as to simulate associated machining processes. The web-based system used VRML.

Angster and Jayaram [2] described the VEDAM (Virtual Environment for Design And Manufacturing) system, which consists of a machine modeling environment (MME), a virtual design environment (VDE), a virtual assembly environment (VAE), and a virtual manufacturing environment (VME). The MME is used for creating models of actual machines; the VDE is an immersive VR environment used to view and modify parametric CAD models; the VAE is used for analyzing the assembly of parts; and the VME is an immersive VR environment used to analyze and develop process plans using a virtual factory. The MME, VDE, VAE, and VME (VEDAM system) interface with the ProE parametric CAD/CAM system through a data integrator and the main interface.

Other research initiatives dealing with VR-based approaches for design and manufacturing applications can also be found in Banerjee and Kesavadas [4].

3 Virtual product design

Virtual product design refers to the use of VPs in product design. VPs can be used to help engineers conceptualize, refine, and modify product designs early in the product development cycle.

A virtual prototyping approach involving the design of dies is elaborated in Kurth and Gadh [26]. While the paper highlights the general complexity of the die design process, it focuses on the "die open" directions problem (the die open directions refer to the directions in which to remove a part from the associated die). The general approach outlined (which has also been implemented using the C++ programming language) uses a target part's geometry and topology (including its features) to determine potential die open directions without a known "parting line," but can only be used for parts containing blind concave features. First, 2-D maps are generated from the 3-D parts followed by identification of features; subsequently, the 2-D maps are converted to three dimensions. The authors highlight the fact that using VPs helps reduce the need to use physical prototypes and, thus, reduces the cost and time involved.

A virtual prototyping approach related to the design of trucks is provided in Ren et al. [32]. A virtual prototype of a suspension/steering system and a tire system was built using a virtual prototyping software called ADAMS®. After creating the appropriate CAD models, the relevant boundary conditions were identified and then used to perform simulations. These simulations are performed before physically prototyping a truck design, which, in turn, reduced the overall product development time and reduced engineering costs. The overall approach and philosophy can be used for a wide variety of engineering life cycle product development applications as well.

The use of virtual prototyping approaches in the design and manufacturing of equipment such as a vertical planetary mill machine is delineated in Li et al. [28]. A planetary mill machine is capable of shearing, extrusion, and grinding actions, which are used to pulverize target particles. After creating the relevant CAD models, ADAMS was used to facilitate the creation of such a virtual prototype, which was used to define kinetic, dynamic, and other characteristics. This paper also provides an overview of the virtual prototyping process involved and outlines the simulation of real-world conditions using a VP. After the validation of such a VP, the analysis results can be used to modify a target design using "what if" strategies.

Deitz [15] reported the development of a virtual environment for designing a mobile offshore base at the Gulf Coast Maritime Research Center (University of New Orleans). The VR-based environment allowed engineers to study various digital mockups of large-sized floating bases and assess their feasibility at various sea states and conditions. A variety of software tools, including Vislab®, dVise®, and ADAMS®, were used in this research activity.

Cecil et al. [8] discussed the development of PANDYA (Fig. 6), which is a virtual environment that supports the design of printed circuit boards (PCBs). PANDYA allows teams of engineers to consider both product and process design issues concurrently; it evaluates a candidate design to determine if potential problems in soldering and placement can occur. It allows user to study assembly (work cell) level alternatives, as well as determining a near-optimal solution (for the assembly sequence generation problem) that is based on the use of genetic algorithms. Various assembly platforms can be considered in PANDYA, including placement alternatives and devices. The impact of a design layout on downstream issues such as placement and testing can also be studied.

Other virtual design systems reported include the Virtual Design Studio [14] and a "virtual workshop" discussed by Barrus [5].

4 Related technologies and other research initiatives

Cecil et al. [9, 10] described an environment called VIRAM (VIRtual Reality environment for the Assembly of Microdevices) as part of an integrated system for microassembly design and analysis (Fig. 7). VIRAM aims at supporting the virtual analysis of assembling micron-sized parts, which are then used to modify/control the physical set of microassembly tasks. This system has been implemented using VRML 2.0 and PERL. The virtual analysis is accomplished using an animation information tracking module, a coordinate placement module, and a path planning mechanism; a virtual world manager interacts with the physical world manager to accomplish the analysis and assembly of target microdevices in an integrated manner.

Various applications involving the use of peripherals and hardware, as well as software, are elaborated by Jayaram et al. [20]. The software tools discussed include Muse (MUSE Technologies Inc.), Avocado (Tramberend [38], the CAVE library (Electronic Visualization Laboratory, the University of Illinois, Chicago), Bamboo and VR Juggler ([6]; the peripherals include haptic devices, stereo displays, audio and input alternatives, position trackers, and high-performance graphics components).

The creation of a VR-based environment (created using VRML and Java) is discussed, which is used to interact

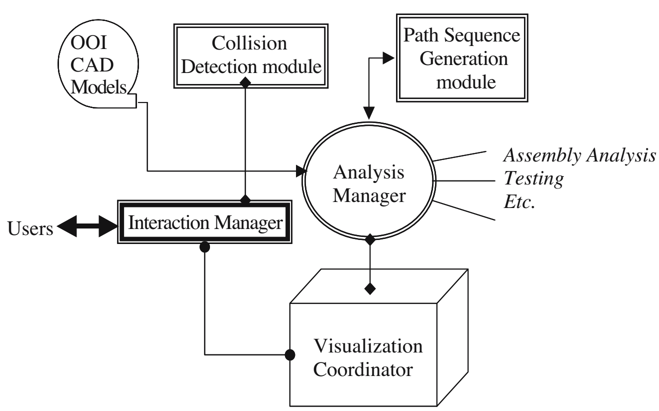
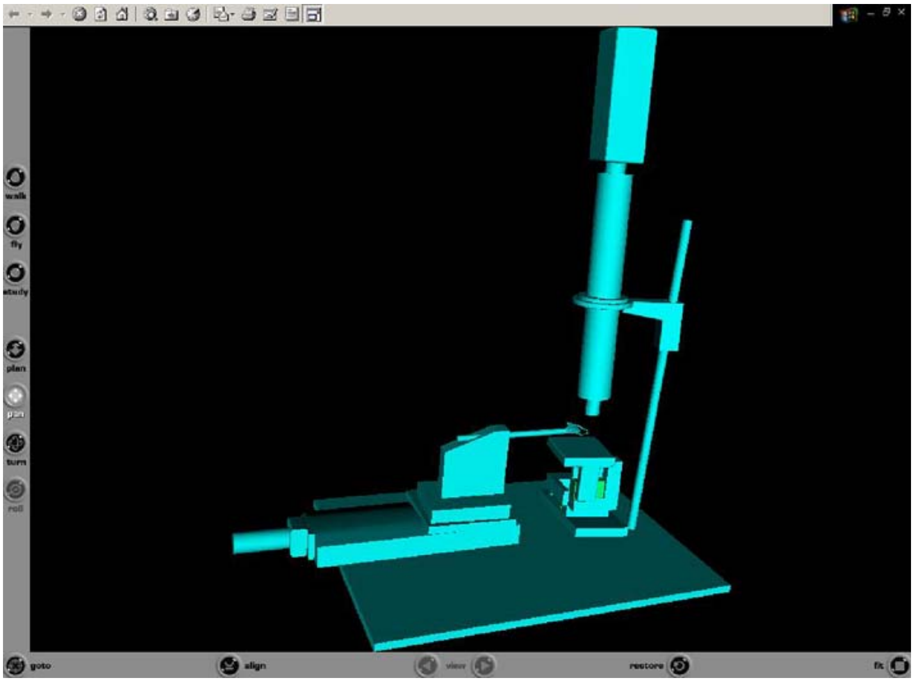


Fig. 6 Architecture of PANDYA

Fig. 7 A view of the virtual environment in VIRAM



with a microassembly work cell [1]. Visual servoing is used to control the microassembly tasks; microassembly involves the assembly of micron-sized parts (1 micron is 10^{-6} m). A user can interact with the virtual environment (such as moving an object, etc.), which is then conveyed to the physical microassembly environment through an interface and software modules.

Zhao [41] proposed the construction of a virtual manufacturing environment composed of five required modules: virtual product modeling; virtual process modeling and planning; virtual instrumentation; data visualization; and virtual shop floor controls. The peripheral interface for this system is Superscape T5 (a VR system from Superscape UK Plc.) with interaction equipment, such as a head-mounted display (HMD), electronic gloves, a 3-D mouse, and other tracking devices. The process for developing this system is based on clustering, coding and classification, and matrix form data assigning, which helps the user create the master environment.

Faisstnauer et al. [17] developed a system which overcomes the problem of inoperability between heterogeneous software and hardware by allowing the different client and server formats to be linked together. The current network using this architecture is the geometry server in the PAVR network, which is a group of 10 European universities that focus on the collaboration of users in computer graphics and animation domains. In this system, there are numerous client and server objects; the server objects commonly store the required information for a scene database, which is modified at runtime by the client objects. The system uses nodes for storing the part geometry data (in VRML format) and the grouping of objects for operational modes.

Leigh et al. [27] described tele-immersion (TI) as a combination of audio and video conferencing using 3-D-image-based modeling with collaborative VR (CVR). This concept allows virtual face-to-face meetings between collaborators at heterogeneous locations in the world via a shared virtual environment. In the system described, the implementation section was developed using CAVERN-Soft from CAVERN (CAVE Research Network). Currently, there are several applications that have been developed using CAVERNsoft. Tele-Immersive VisualEyes at General Motors allows the designers to import 3-D CAD models into the system for design visualization and design reviews. CAVE6D is a tool for the TI visualization of environment data. Motorola uses this technology for developing the test visualization that can provide more details of the test results than the physical drop test that gives only limited data results.

Banerjee et al. [3] proposed a layered architecture for the telecollaboration of virtual manufacturing operations. The three layers include: (1) a virtual lattice (VML) structure layer; (2) an object library layer; and (3) a virtual manufacturing script (VMS) layer. VML is a hierarchical organization which supports the scenegraph structure. VMS is an interaction between the user and the collaborative VR software. VMS is implemented using a script and a parser. The parser reads the script and functions are called to perform a corresponding manufacturing task. The major issues studied during the telecollaboration are network bandwidth, network protocol, network latency and saturation, and packet size. Staadt et al. [37] described another form of collaborative virtual environment system called JAPE, which is a common platform for VR application development that includes support for video acquisition, speech, and interaction devices. This contains the scene graph and data flow, along with the inputs, which allows various applications to be developed with features like the rendering of 3-D images, tracking flexibility, image warping, multiple images, video, and audio.

One of the more advanced immersive VR-based environments is the original CAVE (Cave Automatic Virtual Environment), developed in 1992 by researchers at the University of Illinois' Electronic Visualization Laboratory. CAVE is an immersive, multi-person, room-sized, high-resolution, 3-D video and audio environment. It uses three walls as projection screens and the floor is the fourth projection screen. CAVE uses Flock of Birds transmitters, 3-D magnetic trackers for position tracking, sensors, and stereo glasses for viewing 3-D stereographic images. The types of electromagnetic tracking systems used in immersive visualizations is summarized by Jayaram et al. [20]. These include two categories of tracking (one operates using DC magnetic field, while the other category deals with AC magnetic fields). A discussion of the calibration system needed for measuring and correcting the static errors of DC magnetic trackers is also provided.

Yun et al. [40] discussed hand postures and forces, and defined aspects of the manner an object is grasped in the context of robotic manipulation. A means for specifying these grasping "flavors" that use an instrumented glove equipped with joint and force sensors was described. The feasibility of measuring desired grasp characteristics was demonstrated for a modified Cyberglove impregnated with force-sensitive resistors (pressure sensors at the fingertips). The force sensors used to simulate the grasping action can sense the pressure applied. A detailed study is described, involving multiple users performing various grasping tasks. The effectiveness of using haptic devices in a virtual environment was also studied by Volkov and Vance [39], who underlined the important role of using haptic sensors.

Kim and Vance [25] examined several polygonal-based collision detection packages with the Voxmap Pointshell (VPS) software for the development of a virtual assembly application. VPS is a software developer's toolkit for collision and proximity detection, swept volume generation, dynamic animation, and haptics. A comparison of the various collision detection packages was performed and their results were presented.

5 Discussion and conclusion

This paper presented a detailed literature review on virtual prototyping in design and manufacturing. The usefulness of various related technologies (including haptic sensors) in research initiatives were also reviewed.

Virtual prototyping is a complex process which enables engineers to communicate collaboratively during the product development process, ranging from design, planning, and manufacturing to assembly. Virtual prototypes (VPs) are 3-D computer-based models which facilitate the use of virtual reality (VR) technology and mimic target products or processes. Some of the well documented benefits of adopting virtual prototyping techniques in engineering include the ability to detect design and manufacturing problems early in the product development cycle, support of concurrent engineering approaches to engineering activities, reduction in the lead time involved in manufacturing, as well as developing new products. These benefits translate into reduced overall product development cost and improved product quality.

Although there has been a substantial amount of research in the general area of virtual prototyping, additional research is required in various domain segments. These can be summarized as follows:

(a) Physics-based simulation: In the domain of virtual prototyping for metal cutting operations, there is a need to develop more robust physics-based simulation tools and approaches where the impact of cutting forces, tool material, and related factors are taken into account. Currently, the existing virtual prototyping tools can neither visualize nor predict accurately the quality of the surface finish for a given set of machining conditions. This is an important area of research which needs to be addressed by future research efforts.

(b) Virtual prototyping of microsystems and processes: Another area which needs to be investigated relates to the creation of virtual prototyping environments dealing with the simulation of micro-level technologies and processes (such as the manufacturing processes involved in the production of micro electro mechanical system, or MEMS). Such approaches would seek to provide a high fidelity simulation environment where the impact of materials, operating conditions, presence of catalysts, etc., can be compared, studied, and predicted prior to physically producing the MEMS or microdevices. Currently, while several researchers have created visualizations of MEMS processes, there has been no reported work of advanced virtual environments for simulating these processes and techniques. However, research efforts dealing with the virtual assembly of microdevices have been reported (as discussed in Sects. 3 and 4 of this paper).

(c) Distributed VR and Internet2: There is also a need to explore research issues in distributed virtual prototyping across heterogeneous computing platforms. While several researchers have proposed frameworks to successfully demonstrate these capabilities, there is a need to address issues related to the speed and efficiency of interaction across distributed user sites in a more comprehensive manner. With the emergence of Internet2, there is potential for researchers to explore its feasibility for distributed VR. Internet2, which is the successor of the Internet, is under development by a partnership involving U.S. universities, industry, and the government. Internet2 is intended for the development and deployment of advanced network applications and technologies, including a substantial increase in bandwidth [18].

Acknowledgements Funding for the research activities associated with this paper was obtained through grants from the National Science Foundation (NSF grant numbers 0196303 and 0230709). Professors Shankar Jayaram and Uma Jayaram (Washington State University) provided images pertaining to the VADE virtual reality environment. Professor Kesavadas (State University of New York at Buffalo) provided images of the VR Fact and VPAVE environments. Their assistance and cooperation is gratefully acknowledged.

References

1. Alex J, Vikramaditya B, Nelson BJ (1998) A virtual reality teleoperator interface for assembly of hybrid MEMS prototypes. In: Proceedings of the 1998 ASME Design Engineering Technical Conferences and Computers in Engineering Conference (DETC'98), Atlanta, Georgia, September 1998
2. Angster SR, Jayaram S (1996) VEDAM: virtual environments for design and manufacturing. In: Proceedings of the Symposium on Virtual Reality in Manufacturing Research and Education, Chicago, Illinois, October 1996
3. Banerjee A, Banerjee P, DeFanti T, Hudson A (2000) A behavioral layer architecture for telecollaborative virtual manufacturing operations. IEEE Trans Robotic Autom 16 (3):218–227
4. Banerjee P, Kesavadas T (1999) Industrial virtual reality: manufacturing and design tool for the next millenium. In: Proceedings of the NIST-ASME Industrial Virtual Reality Symposium, Symposium on Virtual Environment for Manufacturing, Chicago, Illinois, November 1999
5. Barrus JW (1993) The virtual workshop: a simulated environment for mechanical design. PhD dissertation, Massachusetts Institute of Technology, Cambridge, Massachusetts
6. Bierbaum A, Just C, Hartling P, Meinert K, Baker A, Cruz-Neira C (2001) VR juggler: a virtual platform for virtual reality application development. In: Proceedings of the IEEE Virtual Reality 2001 Conference, Yokohama, Japan , March 2001, pp 89–97
7. Bodner DA, Damrau M, Griffin PM, McGinnis LF, McLaughlin A (1999) Virtual prototyping of electronics assembly systems. Electron Manuf Eng 14(3):1–5
8. Cecil JA, Kanchanapiboon A, Kanda P, Muthaiyan A (2002) A virtual prototyping test bed for electronics assembly. In: Proceedings of the 27th Annual IEMT/IEEE International Electronics Manufacturing Technology Symposium, San Jose, California, July 2002, pp 130–135
9. Cecil J (2004) VIRAM: a virtual reality environment for the assembly of micro devices. In: Proceedings of the 24th ASME International Computers and Information in Engineering (CIE) conference, Salt Lake City, Utah, September/October 2004
10. Cecil J et al (2005) Development of a physical and virtual work cell to support the assembly of micro devices. Robot Comput Integr Manuf (in press)
11. Cecil J (2003) A virtual prototyping environment for the assembly of nanosatellites. In: Proceedings of the IIE Annual Research Conference, Portland, Oregon, May 2003
12. Chryssolouris G, Mavrikios D, Fragos D, Karabatsou V (2000) Virtual reality based experimentation environment for the verification of human-related factors in assembly processes. Robot Comput Integr Manuf 16:267–276
13. Chung C, Peng Q (2003) The development of a web-centered VR-CAPP system. In: Proceedings of the International Conference on Agile Manufacturing (ICAM 2003), Beijing, China, December 2003, pp 369–376
14. Dani T, Gadh R (1997) Creation of concept shape designs via a virtual reality interface. Comput Aided Des 29(8):555–563
15. Deitz D (1998) Modeling a virtual ocean. Mechanical Engineering Magazine, May 1998, pp 66–68. Available online at: http://www.memagazine.org/backissues/may98/features/ocean/ocean.html
16. Deviprasad T, Kesavadas T (1999) VPAVE: an interactive tool for validating assembly components in virtual environments using finite element simulation. In: Industrial VR: manufacturing and design tool for the next millennium. ASME Press, pp 107–116
17. Faisstnauer C, Purgathofer W, Gervautz M, Gascuel J (2001) Construction of an open geometry server for client–server virtual environments. In: Proceedings of the IEEE VR 2001 Conference, Yokohama, Japan, March 2001, pp 105–112
18. Internet2 (2004) Home page at: http://www.internet2.edu/about/
19. Jasnoch U, Anderson B, Joseph H (1996) Shared 3D environments within a virtual prototyping environment. In: Proceedings of the 5th International Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises (WET-ICE'96), Stanford, California, June 1996, pp 274–279
20. Jayaram S, Vance J, Gadh R, Jayaram U, Srinivasan H (2001) Assessment of VR technology and its applications to engineering problems. J Comput Inf Sci Eng 1(1):72–83
21. Jayaram S, Jayaram U, Wang Y, Tirumali H, Lyons K, Hart P (1999) VADE: a virtual assembly design environment. IEEE Comput Graph Appl 19(6):44–50
22. Jayaram S, Wang Y, Jayaram U, Lyons K, Hart P (1999) A virtual assembly design environment. In: Proceedings of the IEEE Virtual Reality Conference (VR'99), Houston, Texas, March 1999, pp 172–179
23. Kelsick J, Vance JM, Buhr L, Moller C (2002) Discrete event simulation implemented in a virtual environment. J Mech Des–Trans ASME 125(3):428–433
24. Kesavadas T, Ernzer M (1999) Design of virtual factory using cell formation methodologies. In: Industrial virtual reality: manufacturing and design tool for the next millennium, Proceedings of the ASME Symposium on Virtual Reality Environments for Manufacturing, Nashville, Tennessee, November 1999, MH 5, pp 201–208
25. Kim CE, Vance JM (2004) Collision detection and part interaction modeling to facilitate immersive virtual assembly methods. J Comput Inf Sci Eng 4(2):83–90
26. Kurth GR, Gadh R (1997) Virtual prototyping of die-design: determination of die-open directions for near-net-shape manufactured parts with extruded or rotational features. Comput Integr Manuf Syst 10(1):69–81
27. Leigh J, Johnson AE, DeFanti TA, Brown M et al (1999) A review of tele-immersive applications in the CAVE research network. In: Proceedings of the IEEE Virtual Reality Conference (VR'99), Houston, Texas, March 1999, pp 180–187
28. Li R, Fang M, Zhang W, Ma Y (2001) Simulation of vertical planetary mill based on virtual prototyping. J Univ Sci Tech Beijing 8(2):86–90
29. Mikchevitch A, Leon JC, Gouskov A (2004) Flexible beam part manipulation for assembly operation simulation in a virtual reality environment. J Comput Inf Sci Eng 4(2):114–123
30. Mok SM, Wu C-H, Lee DT (2001) Modeling automatic assembly and disassembly operations for virtual manufacturing. IEEE Trans Syst Man Cybern A 31(3):223–232
31. Peng QJ, Loftus M (1999) Analysis of 3D construction approaches to support the virtual manufacturing process. In: Proceedings of the International Conference on Advanced Manufacturing Technology (ICAMT'99), Xian, China, June 1999, pp 653–657
32. Ren W, Zhang Y, Song J (1999) Virtual prototype technology in automotive concurrent design. National Key Laboratory, Automotive Safety and Conservation. Beijing, China
33. Shao Z, Gong YD, Wang WS (2001) Modeling and simulation of virtual grinding machine. Key Eng Mater 202–203:259–264
34. Sharma R, Molineros J, Raghavan V (1997) Interactive evaluation of assembly sequences with mixed (real and virtual) prototyping. In: Proceedings of the IEEE International Symposium on Assembly and Task Planning (ISATP'97), New York, August 1997

35. Siddique Z, Rosen DW (1997) A virtual prototyping approach to product disassembly reasoning. Comput Aided Des 29 (12):847–860
36. Smith RP, Heim JA (1999) Virtual facility layout design: the value of an interactive three-dimensional representation. Int J Prod Res 37(17):3941–3957
37. Staadt OG, Näf M, Lamboray E, Würmlin S (2001) JAPE: a prototyping system for collaborative virtual environments. In: Proceedings of the Eurographics 2001 conference, Manchester, UK, September 2001, vol 20, issue 3
38. Tramberend H (1999) Avocado: a distributed virtual reality framework. In: Proceedings of the IEEE Virtual Reality Conference (VR'99), Houston, Texas, March 1999, pp 14–21
39. Volkov S, Vance JM (2001) Effectiveness of haptic sensation for the evaluation of virtual prototypes. J Comput Inf Sci Eng 1 (2):123–128
40. Yun MH, Cannon D, Freivalds A, Thomas G (1997) An instrumented glove for grasp specification in virtual-reality-based point-and-direct telerobotics. IEEE Trans Syst Man Cybern B 27(5):835–846
41. Zhao Z (1998) A variant approach to constructing and managing virtual manufacturing environments. Int J Comput Integr Manuf 11(6):485–499