A Brief Introduction of VR and AR Applications in Manufacturing

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1.1 Introduction

In the current highly competitive business and manufacturing environment, manufacturing industry is facing the constant challenge of producing innovative products at reduced time-to-market. The increasing trend of globalized manufacturing environments requires real-time information exchanges between the various nodes in a product development life cycle, e.g., design, setup planning, production scheduling, machining, assembly, etc., as well as seamless task collaboration among these nodes. In addition, with increased environmental awareness and legislation, more constraints have been placed on product disposal, hence promoting product recycling, servicing and repairing activities. Product development processes are becoming increasingly more complex as products become more versatile and intricate, and inherently complicated, and as product variations multiply with the trend of mass customization. Thus, manufacturing processes have to be more systematic in order to be efficient and economically competitive. An innovative and effective solution to overcome these problems is the application of virtual reality (VR) and augmented reality (AR) technologies to simulate and improve these manufacturing processes before they are carried out. This would ensure that activities such as design, planning, machining, etc., are done right-the-first-time without the need for subsequent rework and modifications.

Research on the manufacturing applications of VR and AR is a strong and growing area. The challenge is to design and implement integrated VR and AR manufacturing systems that could enhance manufacturing processes, as well as product and process development, leading to shorter lead-time, reduced cost and

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improved quality. The ultimate goal is to create a system that is as good as the real world, if not better and more efficient.

The aim of this book, which is a collection of the state-of-the-art studies of the leading researchers in VR and AR technologies, is to offer the readers an overview of the current and future trends of these technologies and their applications in addressing some of the issues faced by manufacturing industry.

1.2 Background of VR and AR Technologies

1.2.1 VR Technologies

VR can be described as a 4D simulation of the real world, including the 3D geometry space, 1D time and the immersive or semi-immersive interaction interface. Generally, VR can be classified as hardware-based VR and computer-based VR. A hardware-based VR system depends on special VR hardware such as a head-mounted display, VR-glove, etc. A PC-based VR system is implemented using software on personal computers (PCs). It uses standard PC peripherals as input and output tools. Currently, a hardware-based VR system can be considered an immersive virtual scene, whereas a PC-based VR system is semi-immersive. Dedicated VR peripherals are usually too costly for many applications. As PC-based Internet technologies are developing rapidly, they present a promising alternative to hardware-based VR (Luo et al. 2002).

VR applications in mechanical-related areas are quite well established, e.g., virtual layout design, virtual prototyping, Internet-based virtual machining (Qiu et al. 2001; Ong et al. 2002; Zhou et al. 2003), web-based fault diagnostic and learning system (Ong et al 2001), etc. However, one of the research issues in VR applications is the conflicting requirement for high rendering quality and near real-time interactivity.

There are two major methods to implementing a PC-based VR system (Huang et al. 1998). In the image-based rendering method (IBRM), the virtual world builders take photographs of a set of viewpoints to generate a panorama for each viewpoint. The second method is the model-based rendering method (MBRM), where the virtual worlds are constructed using a 3D solid model for each object within the virtual environment. Both methods have their advantages and disadvantages.

The major advantages of the IBRM are:

- It is easy to construct a photo-quality virtual world using the IBRM, and thus an IBRM system produces good realistic effects.
- The complexity of the virtual world construction is constant, regardless of the complexity of the real world modelled.
- It has good real-time interactivity due to low data demand, which depends only on the data of the images.

However, although the realistic quality of an IBRM virtual environment can be very high, it is not really considered to be immersive because it lacks interactivity. The major interaction that an IBRM VR system provides is virtual navigation, which includes functions such as exploring, walking through, etc. The virtual scenes cannot be manipulated because they are constructed with projected images and not solid objects. It is difficult for users to have good immersive feelings in an IBRM virtual environment owing to limited interactivity.

Compared with IBRM, MBRM allows operators to interact with the contents of the virtual environment and thus provides better interactivity. Operators can manipulate the objects in an MBRM virtual scene, such as adding, moving, rotating, etc. However, many disadvantages tend to overwhelm the immersion effect of an MBRM virtual environment. They are:

- Poor realistic effects due to the artificially constructed models.
- The complexity of the virtual world construction is proportional to the complexity of the real world, i.e., it will contain a large amount of data if the real world is complex.
- It has poor real-time interactivity due to the large amount of data to be manipulated. It is difficult to make users feel that they are travelling and exploring the virtual worlds freely if they have to wait for a long time when transiting from one viewpoint to another, or in moving an object.

1.2.2 AR Technologies

AR is a new form of human-machine interaction that overlays computer-generated information on the real world environment (Reinhart and Patron 2003). AR enhances the existing environment rather than replaces it, as in the case of VR. AR can potentially apply to all human senses, such as hearing, touching and even smelling (Azuma 1997). In addition to creating virtual objects, AR could also remove real objects from a perceived environment. The information display and image overlay are context sensitive, which means that they depend on the observed objects. This novel technique can be combined with human abilities to benefit manufacturing and maintenance tasks greatly.

AR technologies are both hardware and software intensive. Special equipment, such as head-mounted devices, wearable computing gears, global positioning systems, etc., are needed. Real-time tracking and computation is a must, since synchronization between the real and the virtual worlds must be achieved in the shortest possible time interval.

Extensive research has been carried out worldwide in addressing some of the critical issues in AR technologies. Commercial hardware and software tools are widely available. Examples are: the ARToolKit for building AR applications, which can be downloaded from the website for free; and dedicated equipment manufacturers, such as MicroOptical, Minolta, Sony, Olympus, MicroVision, etc., that supply the necessary viewing head-mounted displays. Several of the latest studies are reported in the AR section of this book. Some of the pertinent issues are now mentioned.

Registry

Aligning objects accurately in the virtual and real worlds in real-time is one of the challenging issues. This is particularly critical in some of the operations where precise alignment information is required and approximate registration may either cause confusion or error.

Latency

This is sometimes referred to as dynamic errors due to system delay in the tracking and processing of the signal. This contributes to the single largest source of the registration error. For tracking moving objects, motion prediction and switching between multiple models is one means of reducing this error (Chai et al. 1999).

Calibration

Extensive calibration is necessary to ensure high accuracy registry. Presently, there are calibration-free renderers, auto-calibration systems for automatic measurement and compensation of changing calibration parameters (Azuma et al. 2001).

Human Factors

Although many preliminary experimental studies have shown that there is increased productivity in manufacturing operations such as assembly, equipment maintenance and procedural learning, there are significant human factors yet to be overcome. Some of them are: attention tunnelling where a user's attention is only focused on the area cued and is at the expense of other areas, could create potential dangers at work (Tang et al. 2003); fatigue and eye strain due to uncomfortable AR display devices and prolonged usage; difficulty in adjusting to normal vision after prolonged wearing of AR displays, etc.

1.3 Research Issues

1.3.1 VR in Manufacturing

The combination of information technology (IT) and production technology has greatly changed traditional manufacturing industries. Many manufacturing tasks have been carried out as information processing within computers. For example, mechanical engineers can design and evaluate a new part in a 3D CAD system without constructing a real prototype. As many activities in manufacturing systems can be carried out using computer systems, the concept of virtual manufacturing (VM) has now evolved.

VM is defined as an integrated synthetic manufacturing environment for enhancing all levels of decision and control in a manufacturing system. VM is the integration of VR and manufacturing technologies. The scope of VM can range from an integration of the design sub-functions (such as drafting, finite element analysis and prototyping) to the complete functions within a manufacturing enterprise, such as planning, operations and control (Shukla et al. 1996).

VM systems are integrated computer-based models that represent the precise structures of manufacturing systems and simulate their physical and informational behaviour in operation (Iwata et al. 1995). VM technology has achieved much in reducing manufacturing cost and time-to-market, leading to an improvement in productivity. Much research effort to conceptualize and construct a VM system has been reported. Onosato and Iwata (1993) generated the concept of a VM system and Kimura (1993) described the product and process model of a VM system. Based on the concept and the model, a general modelling and simulation architecture for a VM system was developed by Iwata et al. (1995). Ebrahimi and Whalley (1998) developed a cutting force prediction model for simulating machining conditions in VM. A virtual machining laboratory for knowledge learning and skills training was implemented by Fang et al. (1998). In the virtual machining laboratory, both comprehensive knowledge learning and physical skills training can be achieved in an interactive synthetic environment. Using head-mounted stereo glasses and interactive gloves, students can virtually operate a lathe or set machining parameters and input CNC G-code program to cut the work-piece automatically. Machining process performance, such as machining conditions, cutting forces, cutting power, surface roughness and tool life, can also be simulated with the machining process evaluation models.

In addition, some commercial software for VM, such as Delmia's VNC, can simulate machining processes in a 3D environment and detect collision (Delmia 2001). By using a VM system, users can select and test different machining parameters to evaluate and optimize machining processes, and the manufacturing cost and time-to-market can be reduced, leading to an improvement in productivity.

However, a practical VM system is highly multi-disciplinary in nature. Many of these research projects and commercial software for VM systems have restrictions in their implementation. Firstly, many machining theories and heuristics need to be modelled in a VM system. However, most VM applications are designed only for specific problems in pre-defined conditions. There is no one VM application having all the technologies necessary to model a real machining process. Secondly, each constructing process of a new VM system is akin to the reinvention of "wheels". Besides geometrical modelling of machines, analytical modelling of machining parameters, such as the cutting force, also has to be developed for every specific task. Lastly, various VM systems are developed with different programming and modelling languages, making them less flexible and scalable due to incompatibility problems. Any change in one part would require the whole system to be modified.

During a VM simulation process, 3D graphics or VR will be an enabling tool to improve human-to-human or human-to-machine communications. VM addresses the collaboration and integration among distributed entities involved in the entire production process. However, VM is regarded as evolutionary rather than revolutionary. It employs computer simulation, which is not a new field, to model products and their fabrication processes, and aims to improve the decision-making processes along the entire production cycle. Networked VR plays an essential role in VM development.

Current VR and Web technologies have provided the feasibility to implement VM systems. However, this is not an easy task due to the following factors.

- The conflicting requirements of real-time machining and rendering. Generally, a high level of detail for a scene description would result in a high complexity of the virtual scene.
- The conflicting requirements of static data structure and dynamic modelling. In the virtual machining environment, a dynamically modelled workpiece is essential.
- The requirements for a consistent environment to avoid confusion and provide navigational cues to prevent a user from getting lost in the VR environment.
- The importance of an adequate sense of immersion in the VR environment, without which even a highly detailed rendering will not help a user interact effectively in the virtual 3D environment using conventional 2D interfaces such as a keyboard.

1.3.2 AR in Manufacturing

Manufacturing tasks such as product assembly and system maintenance are usually information intensive and time consuming. The training of personnel to perform such tasks can be tedious and unproductive. Although it has often been mentioned that VR technology is used in the early phase of the life-cycle of an assembly station, whereas AR is more in the control and maintenance phase (Reinhart and Patron 2003), AR can also be used effectively in assembly planning operations.

AR can enhance a person's perception of the surrounding world and understanding of the product assembly tasks to be carried out. Using an AR approach, graphical assembly instructions and animation sequences can be pre-coded at the design stage for typical procedures. These sequences can be transmitted upon request and virtually overlaid on the real products at the assembly lines as and when they are needed. The instructions and animations are conditional and can be automatically adjusted to actual conditions at the assembly lines. These instructions and animated sequences can be updated periodically with updated knowledge from the manufacturers. This approach can reduce the information overload and the training required for assembly operators. It can reduce product assembly time, thus reducing product lead-time. Tang et al. (2003) compared three instructional media in an assembly system: a printed manual, computer-assisted instruction (CAI) using a monitor-based display and CAI using a head-mounted display. They found that, by using overlaying instructions on actual components, the error rate for an assembly task was reduced by 82% (Tang et al. 2003). Other well-known applications of AR in the assembly domain are Boeing's cable harness assembly project (Caudell and Mizell 1992), car door assembly (Reiners et al. 1998), furniture assembly (Grimm et al. 2002), and assembly of cockpit modules (Alt and Schreiber 2001).

Apart from the assembly and maintenance operations that could benefit from AR applications, collaborative applications such as multiple people simultaneously viewing, discussing and interacting with 3D models in an AR environment, either in one location or remotely, could produce smooth and seamless integration of existing manufacturing practices and activities (Azuma et al. 2001). A Virtual Round Table concept for collaboration between multiple users was also reported by Broll et al. (2000). Several other reported systems are briefly mentioned here.

- The Studierstube system (Szakavari et al. 1998) was developed at the Technical University of Vienna. A Personal Interaction Panel (PIP) as a new input device was introduced.
- The TransVision System (Rekimoto and Nagao 1995) by the Sony Computer Science Laboratory used palmtop computers as display units instead of head-mounted displays.
- DigitalDesk (Wellner 1993) used direct computer-based interaction with selected portions of documents.
- The BUILD-IT system (Rauterberg et al. 1997) supports engineers in designing assembly lines and building plants based on a table-top interaction area.

1.4 General Themes of This Book

The aim of this book is to present a state-of-the-art overview of VR and AR research in manufacturing applications. This book focuses on the applications of VR and AR technologies in solving and enhancing manufacturing processes and systems, and gives sample research issues in both academia and industry. The book is organized into two parts, namely, the VR technologies and applications and the AR technologies and applications in manufacturing.

In part one, solid modelling in a VR environment via constraint-based manipulations and through haptic interfaces is presented separately by Zhong and Ma, and Peng and Leu. Zhong and Ma present a hierarchically structured high-level constraint-based data model for precise object definition, a mid-level CSG/BRep hybrid solid model for hierarchical geometry abstractions and object creation, and a low-level polygon model for real-time visualization and interaction to support solid modelling in the VR environment. Constraints are embedded in the solid model and organized at different levels to reflect the modelling process from features to parts. Solid modelling in their VR environment is performed in an intuitive manner through constraint-based manipulations. Peng and Leu, on the other hand, handle this intuitive modelling issue with a haptic interface in their virtual sculpting system. The VR interface includes stereo viewing and force feedback. Dexel representation, image-space Boolean operation, and haptic rendering are utilized and integrated to develop the system that enables a user to sculpt a virtual solid interactively.

On the application of VR in manufacturing, four applications of VR in assembly and disassembly processes, verification and analysis of maintenance and assembly processes, product scheduling, and in manufacturing system simulations are presented. Akgunduz and Banerjee have developed an efficient technique for managing and distributing data in a VR system. A data-traffic controller has been developed to distribute data in large-scale collaborative VR environments. They have identified an interesting aspect in data management in VR simulations, which is the delay in data transmission to a particular user in a collaborative VR environment when this user is not in the viewing range of the VR simulation. These delays, when well scheduled and managed, can significantly reduce the data transmission load. Banerjee et al. integrate a VR environment with a Petri Net-based manufacturing control to enhance the visualization of the operations of a flexible manufacturing cell (FMC), as well as to improve the control of the manufacturing processes in this FMC. In assembly and disassembly processes, Chryssolouris et al. report on a hybrid approach to verify and analyze assembly and maintenance processing using VR and digital mannequin technologies, Ikonomov and Milkova report on the use of natural human interaction and control in a VR system for assembly and disassembly to help product designers improve their products before the products are produced. The models in their system are able to respond and behave in the same way as real objects and machinery, with sounds and force feedback.

Part two of this book presents some hardware developments and the software and human factors issues of AR applications in manufacturing. With regard to AR software issues, Vacchetti et al. combine a powerful VR framework with computer vision techniques to form an AR system for training and planning in an industrial environment. The resulting AR system is capable of producing complex rendering and animation of virtual human characters that can be blended into the real world. Robertson and MacIntyre observe that AR needs to account for the fact that registration will never be perfect, and that, indeed, it will vary depending on available tracking technology. Thus, AR systems need to provide augmentation strategies as a function of varying registration accuracy. They put forth a postulation that augmentations need to be parameterized according to registration accuracy. Different accuracy requirements will trigger different augmentation styles. Fründ et al. develop a prototype of an AR-based construction set containing elements such as machine tools, robots, etc., that can be transported to a real environment with a user interface to augment the reality. The realization of such an AR-based construction set will be very helpful in developing AR technologies for manufacturing applications, as this construction set could shorten the development times considerably. Rolland's team, on the other hand, have designed and developed a prototype of an optical see-through display using projective display technology and two cameras to acquire images of the user's face. The optics consists of an "ultra light and compact lens system" that was formerly designed and implemented for 52° field of view (FOV). The new development is the 70° FOV optics for projection.

In manufacturing and service applications, Baratoff and Regenbrecht report on the research at DaimlerChrysler in the development and applications of AR technology in the design, production, service and training arenas. A range of AR applications that support several stages of the product life cycle are described to illustrate the use of AR technology in many areas in product development at DaimlerChrysler. In machine tools service and maintenance, Weck et al. develop an AR application for service and maintenance of complex machine tools that allows hands-free operations. Their AR application is based on the ARVIKA project.

AR applications are by far most popular in manufacturing parts handling and assembly activities. Huang et al. develop an AR system to validate the 3-D dynamic simulation of a parts feeding system by augmenting virtual objects with real images of an experimental background. Specifically for parts assembly and disassembly, Molineros and Sharma consider the problem of scene augmentation in the context of a human engaged in assembling an object from its components, and utilize concepts from robot assembly planning and computer vision techniques to develop a systematic framework for presenting augmentation stimuli for the assembly domain without special markers. Tang et al. have conducted experiments to assess the relative effectiveness of AR instructions in computer- assisted assembly with three traditional instructional media approaches. They found that an AR system for computer-assisted assembly can improve worker performance.

Manual welding leads to very high demands of the welder, mainly because of high radiation and poor visibility of the welding scene. Echtler et al. report on a prototype design and implementation of an intelligent welding gun, which is a tracked welding gun equipped with a display that helps welders to navigate, locate and shoot studs with high precision in experimental vehicles. The setup has been tested by a number of welders at the BMW plant. Hillers et al., on the other hand, have developed an AR system using a new welding helmet to improve the view of the welder during manual arc welding. The scene is acquired by taking advantage of a stereoscopic high dynamic range complementary metal-oxide semiconductor camera system to provide a wide nonlinear dynamic range of $1{:}10^6$ concerning the light sensitivity, whereby a direct observance of the welding arc and the environment is possible simultaneously.

1.5 Summary

VR technologies are relatively more mature, AR development is really only in its infancy. Driven by the promising success of initial AR prototyping systems in both academia and industry, greater effort to forge widespread applications in the manufacturing industries is clearly foreseeable. Training activities in assembly, machining, welding, inspection and maintenance operations will prove to be most appropriate and beneficial, as the combination of human-machine cognition and intelligence is able to overcome the increasing complexity of product design, processes and equipment. A collaborative AR environment in round-table meetings, seamless integration of product life cycle activities, and designing products right-the-first-time are some of the other apparent benefits.

While all the reported benefits appear to be highly promising, one must not forget the long-term side effects of the users of AR equipment and the immersion in the AR environment, the social acceptance and the health hazards that may be imposed upon them. Some of the ergonomic and social questions are still open issues to be resolved through the development of lighter and better AR hardware and more palatable appearance to users.

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