

A CAVE-based Multi-Material Virtual Prototyping System

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ABSTRACT

This paper proposes a CAVE-based multi-material virtual prototyping (CMMVP) system for immersive stereoscopic visualisation and optimisation of multi-material layered manufacturing (MMLM) processes. The CMMVP system consists mainly of a suite of software packages for simulation of MMLM processes, integrated with a multi-screen CAVE-based virtual reality (VR) system, to create an immersive virtual environment for digital fabrication of multi-material product prototypes. In comparison with desktop-based or semi-immersive VR systems, the CMMVP system blocks out environmental disturbances such that designers can fully immerse in performing stereoscopic visualisation and quality analysis of the resulting multi-material prototypes for subsequent improvements of a product design. The CMMVP system facilitates advanced product design and helps reduce product development time and cost substantially.

Keywords: CAVE; immersive virtual reality; stereoscopic visualisation; multi-material; virtual prototyping; layered manufacturing

1. INTRODUCTION

A multi-material virtual prototyping (MMVP) system [1] has recently been developed for digital fabrication and visual analysis of multi-material prototypes to facilitate product development. The MMVP system consists of a suite of algorithms for simulation of multi-material layered manufacturing (MMLM) processes, which are integrated with a semi-immersive virtual reality (VR) system for stereoscopic visualisation and analysis of the resulting digital prototypes. The semi-immersive VR system may be a desktop display or an LCD projector with a large screen.

The MMVP system fabricates digital multi-material prototypes to help raise the productivity of MMLM machines and improve prototype quality through visualisation of the influences of the critical process parameters. The resulting digital prototypes can be sent via the Internet to customers to solicit comments, while the process parameters can be used for optimal fabrication of physical prototypes. This approach significantly reduces the number of costly physical prototypes needed for product development. Therefore, the associated manufacturing overheads and product development cycles may be reduced substantially, because digital prototypes are mostly used and there is no worry about the costs and the quality of physical prototypes.

A pair of shutter glasses An infrared emitter



Fig. 1. A desktop virtual reality system.

Currently, the MMVP system is integrated with a desktop-based VR system that consists mainly of a PC, a monitor, a pair of shutter glasses, and an infrared emitter, as shown in Fig. 1. It was developed with Visual C/C++ and WorldToolKit Release 9. A pair of shutter glasses generates a stereoscopic feeling by synchronizing with the display device to switch on and off the images to the left eye and the right eye alternately. This creates a depth perception and therefore an illusion of “being there”. Hence, several designers can each wear a pair of shutter glasses to visualise the digital prototype at the same time. This allows a design team to communicate and exchange ideas. However, an obvious limitation of such a semi-immersive desktop-based VR system is that designers are susceptible to environmental disturbances, diminishing their true feeling and concentration in the design process. As a result, they cannot fully immerse in the virtual environment to study and improve the product design efficiently.

To alleviate such weaknesses, the MMVP system is therefore integrated with a CAVE-based VR system with multiple screens to provide an immersive virtual environment for vivid visualisation and interaction in a natural way [2-3]. The design team can fully immerse in exploration, study, and improvement of a product design, including assemblies, sub-assemblies, and components, well before they ever exist physically in reality. Hence, product development cycles and costs can be further reduced [4].

2. THE CAVE SYSTEM

The Cave Automatic Virtual Environment (CAVE) system, which provides a multi-person, room-sized, 3D video and audio environment, was first developed by the Electronic Visualisation Laboratory (EVL) of the University of Illinois-Chicago [5]. Stereoscopic images are projected onto three walls and the floor and are viewed with active stereoscopic glasses equipped with a location sensor. Its main feature is an immersive virtual environment for multiple users exploring the concept of reality and human perception in a real-time perspective.

The CAVE system has been widely applied for visualisation of scientific and technical data sets [6]. For medical applications, doctors used the CAVE system for treatment of patients and planning and training purposes. The VR treatment made it easier for doctors to control operations, and permitted replication of exposure to feared experiences [7]. For military applications, the CAVE system was used by the USA army to design, test, and review new vehicle models before physical fabrication was committed. The development time and cost could be significantly reduced because design errors were reduced as communication between design team members was improved through immersive visualisation of the digital vehicle prototypes in lieu of the physical ones [4, 7]. For commercial applications, some enterprises used the CAVE system to improve their product design, development, and manufacturing processes, and their productivity and effectiveness were improved [4]. Such applications illustrate that the CAVE system is a highly versatile VR platform for immersive visualisation; and it is desirable to extend the existing CAVE system to explore its potential applications at affordable costs.

Therefore, this paper proposes a CAVE-based multi-material virtual prototyping (CMMVP) system that provides an immersive virtual environment for stereoscopic visualisation and optimisation of MMLM processes. This helps reduce product development time and cost substantially, because design errors may be minimised by improved communication between design team members through vivid visualisation and analysis of the resulting product prototypes in an immersive virtual environment.

3. THE PROPOSED CAVE-BASED MULTI-MATERIAL VIRTUAL PROTOTYPING SYSTEM

Based on the conventional ELV CAVE system, a CAVE-based VR system, called imseCAVE, was recently developed in IMSE Department at the University of Hong Kong [8]. It is natural and beneficial to integrate it with the MMVP system to form the proposed CAVE-based multi-material virtual prototyping (CMMVP) system for immersive visualisation and optimisation of MMLM processes.

Fig. 2 shows the flow of the CMMVP system. It begins with loading CAD or MRI/CI models in STL format into the MMVP system, which subsequently performs slicing, hatching, and multi-toolpath planning, and outputs the geometric and material information into a modified common layer interface (CLI) file [9-11]. Next, a translator written in Visual C++ translates the geometric and material information stored in a CLI file to a dataset for a set of CAVE-based VR simulation algorithms created with the Virtools™ Dev software [12]; the dataset is then processed and subsequently the resulting digital prototype is projected on the screens of the imseCAVE. Finally, the digital prototype may be manipulated and studied in the immersive virtual environment created by the system. The following sections describe how the MMVP system is integrated with the imseCAVE to form the proposed CMMVP system.

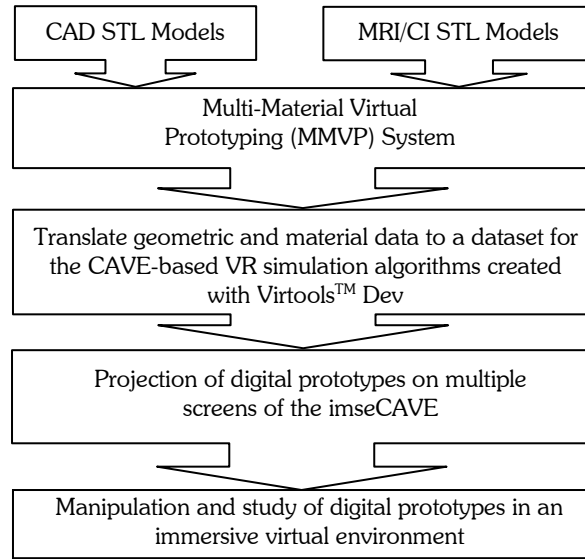


Fig. 2. The flow of the proposed CAVE-based multi-material virtual prototyping system.

3.1 Architecture and Features of the imseCAVE

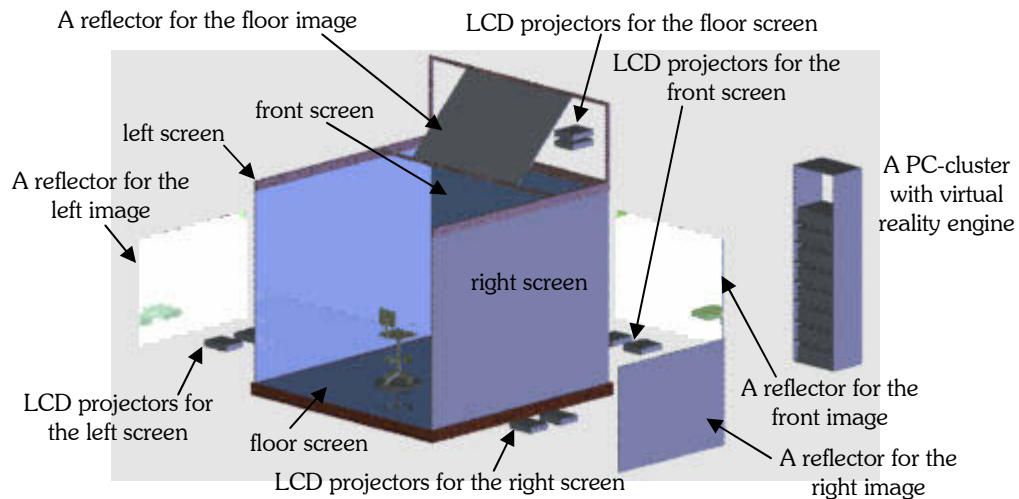


Fig. 3(a). The architecture of the imseCAVE.



Fig. 3(b). The physical construction of the imseCAVE.

Fig. 3(a) and Fig. 3(b) show respectively the architecture and the physical construction of the imseCAVE. It may be regarded as a cubicle with three walls on a floor in which an immersive environment is created by projecting stereoscopic images onto three 10ft x 8ft screens on the walls, namely, the front, the right, and the left, respectively, and on a 10ft x 10ft screen on the floor. Each projection screen has a reflector and two LCD projectors controlled by two related PCs. The LCD projectors are specially designed with polarising lenses to produce high-resolution stereoscopic images. A VR engine, consisting of a cluster of network PCs, coordinates the projectors to project images on the related screens to create an immersive environment. This configuration forms a relatively low-cost, configurable, and flexible CAVE-based VR system, which can be conveniently integrated to form the proposed CMMVP system to facilitate advanced product development.

3.2 Integration of the CAVE-based MMVP System

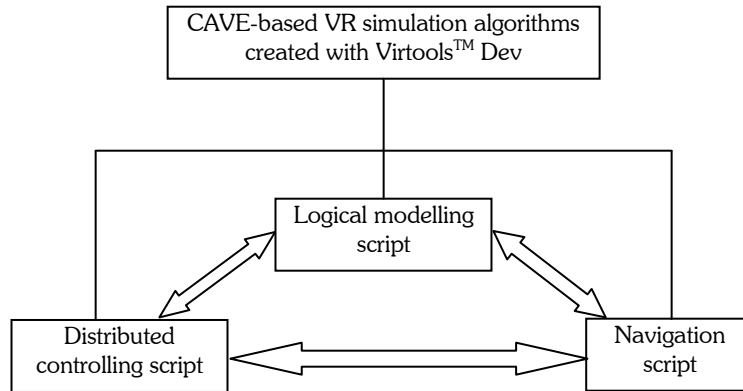


Fig. 4. The main script blocks of the CAVE-based VR simulation algorithms.

The MMVP system is integrated with the imseCAVE to form the CMMVP system by a set of CAVE-based VR simulation algorithms through three control script blocks, as shown in Fig. 4. These script blocks are the logical modelling script, the distributed controlling script, and the navigation script, respectively. They are developed with the Virtools™ Dev software, which contains a suite of algorithms to help programmers create, visualise, manipulate, and track objects in the virtual environment; besides, the Virtools™ VR pack allows users to tailor applications for producing fully immersive, full-life experiences using the PC-based distributed computing. For the Virtools™ Dev software, a *Script* is the visual representation of a behaviour applied to an element. A behaviour is described with *Behaviour Building Blocks* (BBs) which are a visual representation of a software element known as a function. The software provides a collection of predefined BBs that enable users to create an application script conveniently. Scripts are performed by the *Behaviour Engine*. Therefore, using such tools, the proposed three control script blocks can be created accordingly. The following describes these script blocks briefly.

The logical modelling script block interfaces with the MMVP system such that the data for digital fabrication of prototypes stored in a CLI file, including geometric and material information, is translated into a dataset. Subsequently, the logical modelling script loads the dataset into the Virtools™ Dev environment to simulate the prototype fabrication process layer by layer. The logical modelling script block consists mainly of two scripts: one for loading the dataset, namely *DataLoad*, and another for building 3D models for simulation of the prototype fabrication process, namely *Build3DModel*, respectively. The script *DataLoad* consists of two BBS, called *Array Load* for loading the tabular data in cells into an array from the formatted file and *Activate Script* for activating a script, respectively. The two BBS are linked together with *behaviour links* (bLinks). Each BB has its own parameters. While the *DataLoad* script finishes the loading of data, the *Activate Script* BB is immediately triggered to activate the *Build3DModel* script via a *behaviour link* (bLink). Then, the *Build3DModel* starts simulating the prototype fabrication process layer by layer. The system uses a dixel-based approach for simulation of the prototype fabrication process [13, 14]. In order to model a dixel-based prototype, the system uses an object *Cube*, which is a standard 3D entity data resource and is stored in NMO file format, to represent a dixel with its specific position, size, and material property. Hence, three BBS, namely

Set Position, *Scale*, and *Set material*, are used to represent the position, size, and material of a dixel based on the data stored in a text file. In addition, the *Iterator BB* is used to control the layer-by-layer loop process. Fig. 5 shows the digital fabrication process of a multi-material prototype of a toy.

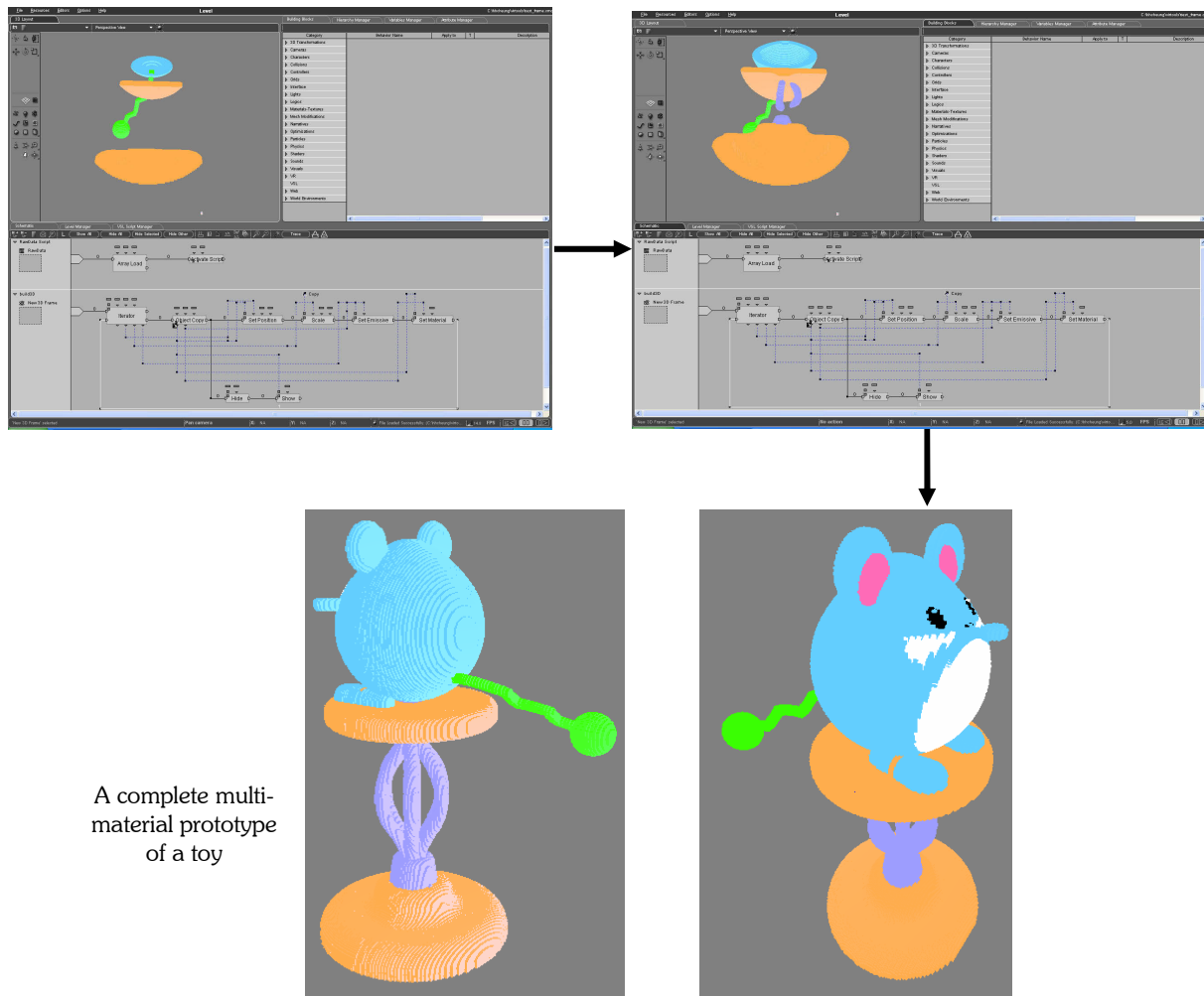


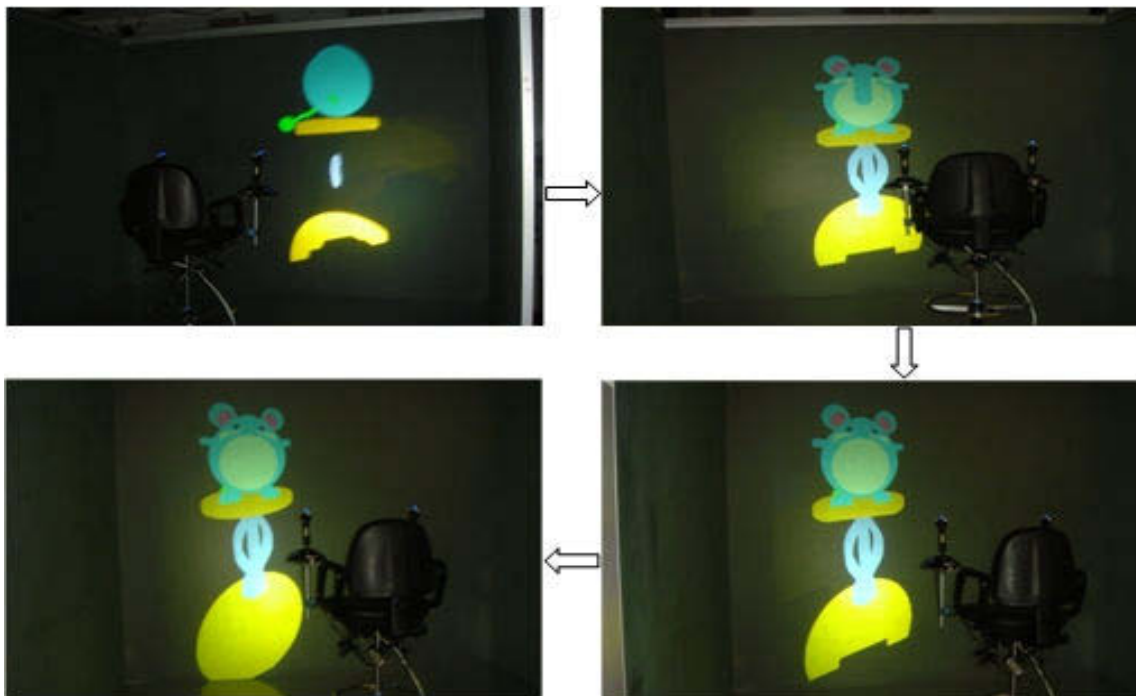
Fig. 5. Digital fabrication of a multi-material prototype of a toy in the Virtools™ Dev environment.

In order to display the resulting digital prototype on the multi-screen CAVE and to provide interactions with it, a distributed controlling script block and a navigation script block are developed and integrated with the logical building script block.

The distributed controlling script block is created using the Virtools™ VR pack, which provides a set of VR libraries containing a package of standard BBs for users to develop applications needed to control a cluster of PCs and projectors. Based on the VR libraries, an application may be conveniently developed by dragging and dropping the BBs and linking together specific input and output ports of the BBs in a visual programming environment. The distributed controlling script block synchronises a cluster of PCs for distributing image signals to the related projectors for projection on the screens, and hence the creation of an immersive virtual environment. This script block also responds to interactions such as translation, rotation, and zoom operations.

The navigation script block controls external input devices, such as a joystick, a keyboard, a mouse, and tracking devices, to handle interactions between users and graphical models in real time. The Virtools™ Dev provides a series of standard script blocks for programmers to create such navigation functions through the graphical interface of a schematic editor. Currently, the navigation script block is able to rotate, zoom in/out the models using a joystick. As the Virtools™ Dev is an object-oriented and event-based programming software, advanced interactions, such as collision detections, and force-feedback feeling, may be integrated conveniently when deemed necessary.

Under the Virtools™ Dev environment, the three control script blocks above are integrated with the MMVP system with the hardware to form the proposed CMMVP system, which simulates the MMLM processes and subsequently displays the resulting digital prototype through the VR engine on the multi-screen cave. With this system, designers may fully immerse in the virtual environment to visualise, manipulate, and explore the resulting multi-material digital prototypes conveniently. Hence, the design concept of a new product can be studied thoroughly and improved effectively.



A complete multi-material digital prototype of a toy



Rotating the prototype for a different perspective

Rooming in the prototype for a closer view

Fig. 6. Digital fabrication of a multi-material prototype of a toy with the CMMVP system.

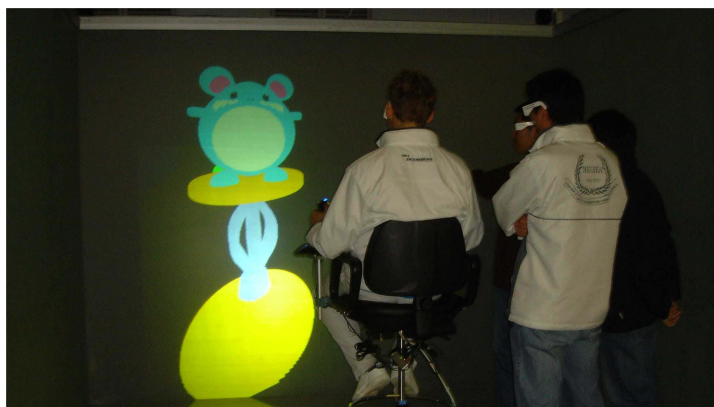


Fig. 7. Immersive environment enhances design collaboration.

Fig. 6 shows the digital fabrication process of a multi-material prototype of a toy in the immersive virtual environment created by the CMMVP system. The resulting prototype can be rotated or zoomed in/out for stereoscopic visualisation from different perspectives in real time. The immersive virtual environment blocks off disturbances so that users may fully focus on studying the prototype, as if manipulating a physical one. Besides, design team members, as shown in Fig. 7, can participate and interact when studying the prototype to evaluate and test the product design effectively before commitment to physical fabrication is made. Hence, the design-prototype-test iteration can be repeated effectively until an optimal design is obtained without incurring any costs associated with physical prototypes. This approach enhances team collaboration that leads to early detection of potential design deficiencies, and hence minimises subsequent production problems. Therefore, the product development time and cost can be reduced substantially.

4. CASE STUDY

Product development time and cost are two major factors that influence the profit margin of an enterprise. In order to reduce product development cost and time, most manufacturers in Hong Kong have adopted various advanced technologies, including 3D solid modelling systems (e.g. SolidWorks, CATIA, and Pro/ENGINEER), and layered manufacturing technology (e.g. 3D Printing, Stereolithography, Selective Laser Sintering, and Fused Deposition Modelling). Using a 3D solid modelling system, a new product or assembly can be designed according to the customer and technical requirements. Subsequently, the CAD model can be sent to a layered manufacturing machine to produce prototypes quickly for design evaluation, and as master patterns for production tools. Hence, the product development time can be reduced.

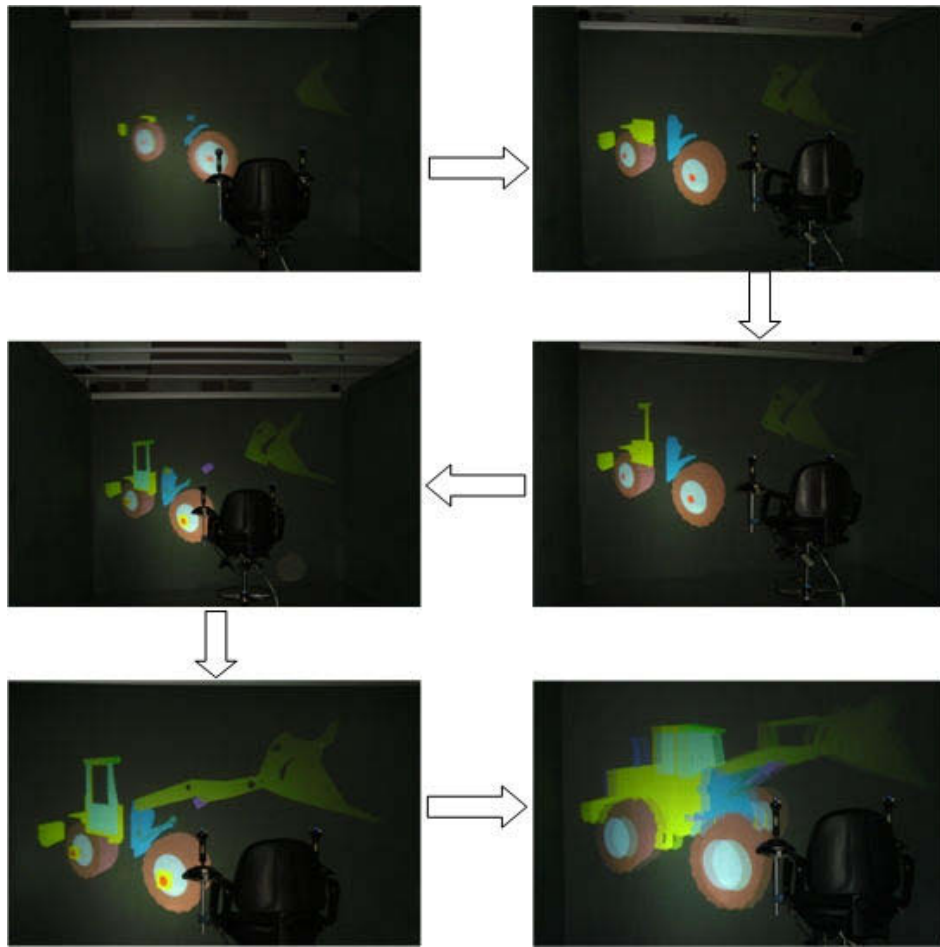
However, layered manufacturing machines are relatively expensive and production of physical prototypes is still a tedious and costly undertaking. Indeed, minimising the use of physical prototypes is an effective way to cut product development time and cost. Therefore, it is desirable to fabricate digital prototypes in lieu of physical ones for design evaluation and testing. The proposed CMMVP system is deemed useful for the manufacturing sector, particularly the toy industry, to achieve the purposes above. A toy excavator is therefore used to demonstrate a possible application of the CMMVP system.

4.1 A Toy Excavator

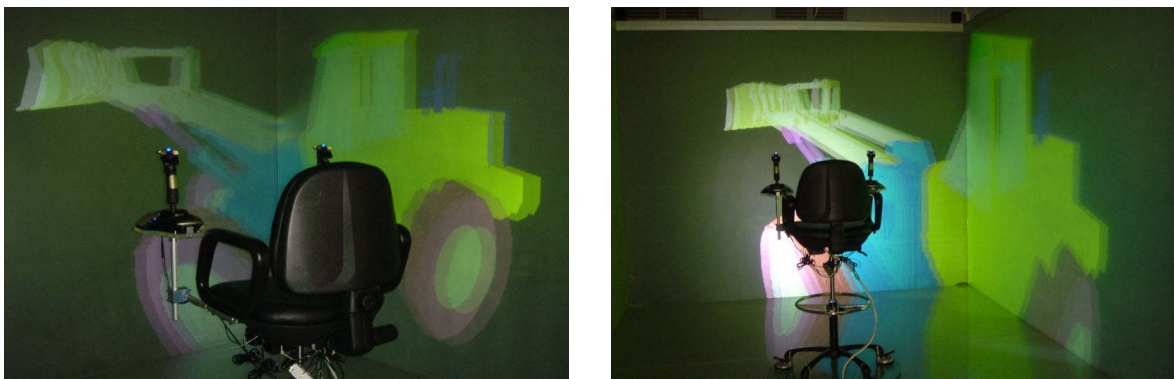
Firstly, SolidWorks is used to create a 3D solid model of a toy excavator; the solid model is then converted to the STL format. Secondly, the CMMVP system loads the STL model to generate geometric and material information for subsequent VR simulation. Finally, the CAVE-based VR system simulates the MMLM process and displays the resulting digital multi-material prototype of the toy excavator in an immersive virtual environment, as shown in Fig. 8.

With the CMMVP system, design team members can immerse in the virtual environment and focus on the evaluation and analysis of the prototype, shown in Fig. 9. They can simultaneously visualise and manipulate the prototype as if using a physical one; at the same time, they can have free discussions about the product design and help improve it accordingly. As a result, design errors may be reduced or avoided in the early stage. When the simulation ends, a set of acceptable process parameters such as orientation, layer thickness, and hatching space can be obtained for the

subsequent fabrication of physical prototypes. Therefore, product development cost and time can be significantly reduced.



A complete multi-material digital prototype of a toy excavator



Stereoscopic visualisation of the excavator prototype from different perspectives

Fig. 8. Digital fabrication process of a multi-material prototype of the excavator in an immersive virtual environment in the imseCAVE.



Fig. 9. Immersive environment enhances collaboration among design team members.

5. CONCLUSIONS

A CAVE-based multi-material virtual prototyping (CMMVP) system has been developed for immersive stereoscopic visualisation and optimisation of multi-material layered manufacturing (MMLM) processes. The multi-material virtual prototyping (MMVP) system is integrated with a multi-screen CAVE-based virtual reality system by three control script blocks developed with the Virtools™ Dev software. The CMMVP system allows designers to create, visualise, manipulate, and track digital multi-material prototypes of a product design in an immersive virtual environment. It blocks out environmental disturbances and allows designers to focus fully on analysing and improving the product design. Hence, product development time and cost can be reduced substantially. The CMMVP system is a flexible and versatile tool for the manufacturing sector. It may be further enhanced as a web-based system to facilitate collaborative product development on a global basis.

6. ACKNOWLEDGEMENTS

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