

# Development of a Virtual Training Workshop in Ultra-precision Machining\*

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*This paper presents the development of a virtual training workshop (VTW) for supporting training of engineering personnel to acquire the theoretical know-how, practical skills and the problem troubleshooting techniques on the usage of ultra-precision machining and inspection facilities, which might not be affordable in conventional training workshop. The architecture, underlying theoretical basis and implementation aspects for the development of the VTW are described. Experimental work for realizing the capability of VTW together with the future development of a distributed virtual training environment (DVTE) are also discussed.*

## INTRODUCTION

THE ACQUISITION of skill through education and training has long been acknowledged as one of the principal forces driving economic growth. Effective training programs can result in increased productivity and quality [1]. Virtual Reality (VR) technology has been used in various forms in training systems for many years, especially for military applications, flight training, equipment operating training, surgical techniques simulating, etc. Ultra-precision machining based on single-point diamond turning is a machining process making use of a mono-crystal diamond cutting tool which possesses nanometric edge sharpness, form reproducibility and wear resistance. The process is capable of producing components with micrometer to sub-micrometer form accuracy and surface roughness in the nanometre range [2]. The success of the technology does not only rely on the sophisticated machine design and control but also depends on its associated nano-metrology. However, ultra-precision machining and nano-metrology are expensive processes. The skill and techniques incurred in the operations of these sophisticated facilities are complex. These demand a well-trained and high skillful operator to operate the ultra-precision machining and nano-metrology facilities. Since any faults in the operation of the ultra-precision machine and measuring equipment might lead to fatal damage and great loss of the expensive facilities or even hazard to the operators, it might not be affordable to conduct conventional workshop training on the use of the ultra-precision facilities.

Virtual reality (VR) has been recognized as an indispensable tool for developing interactive training tools for skills and knowledge training. Examples can be found in the use of flight

simulators for conducting training for the pilots. However, relatively little research has been found in the development of VR as an enable training tool for ultra-precision machining and nano-metrology.

In order to provide a VR environment for interactive user interface and for conducting training, a virtual training workshop (VTW) is purposely built based on the theoretical background of a virtual machining and inspection system proposed by the authors [3]. The VTW will provide an interactive 3D graphic interface for the operator to simulate the diamond turning and surface integrity measuring processes. The use of VR techniques [4] allows individuals to become immersed in a computer-simulated environment that mimics the real operation of the ultra-precision machine and inspection equipment. The user or trainee can practice all necessary switching operations, procedures and skills in a complete safety, while maintaining a high degree of realism. In addition, they can acquire the theoretical know-how of ultra-precision machining and surface metrology as well as develop the problem troubleshooting techniques (Fig. 1). In this paper, the architecture, the underlying theoretical basis and implementation issues for the development of the virtual training workshop are highlighted. The experimental work and applications of the VTW are also discussed.

## THE VIRTUAL TRAINING WORKSHOP (VTW)

### *The architecture of the VTW*

As shown in Fig. 2, the VTW is basically composed of five functional modules which are the control console, the information module, the virtual environment simulator, the event processing module and the virtual objects, respectively. The control console provides the interactive graphic interface for the users to input the control

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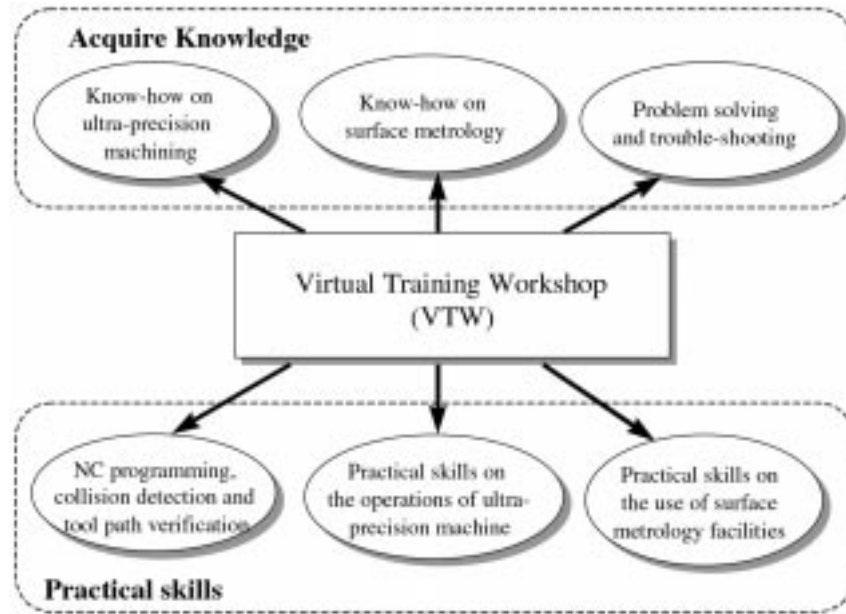


Fig. 1. Functions of the virtual training workshop.

command, NC program, product and tooling information. The user inputs are processed and the corresponding events are ordered sequentially by the event-processing module. The outputs of the module are the control command for the virtual environment simulator and the machine models. Based on the control command issued by the event-processing module and the internal database, the virtual objects simulate the machining and inspection operations. The virtual environment simulator makes use of the control commands from the event-processing module, information module as well as the virtual objects

to mimic the real-world scenarios in the training workshop.

*Control console*

The control console is the graphic user interface in which the user interacts with the virtual environment. Fig. 3 shows the snapshot of control panel of the virtual Nanoform 300 ultra-precision machine. It consists of ‘press buttons’, ‘selecting knobs’, ‘screen’, etc. During the training process, the user can adjust and control the activities of virtual machine tool via operations of these ‘press buttons’ and ‘selecting knobs’ on control panel.

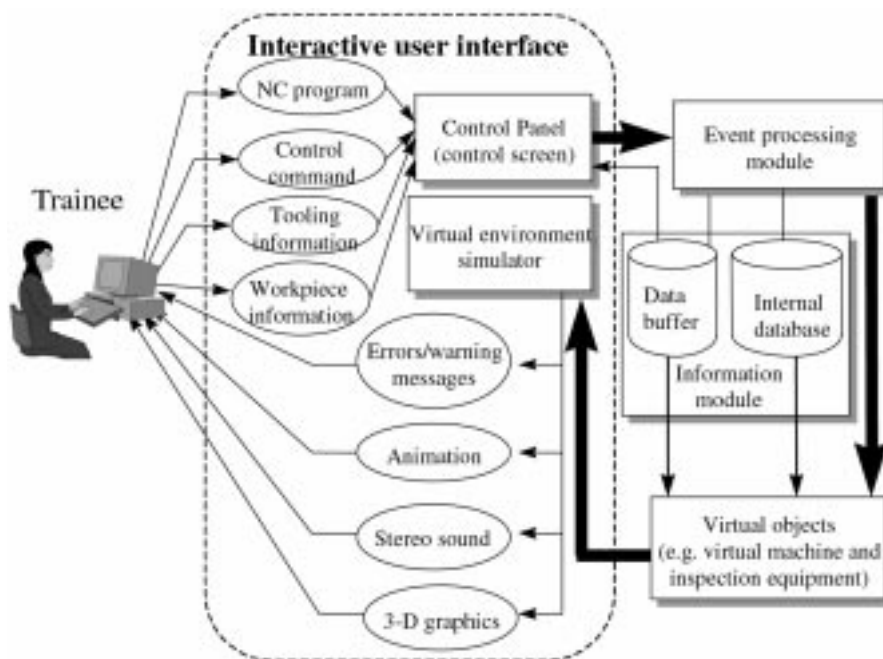


Fig. 2. Framework of the VTW.

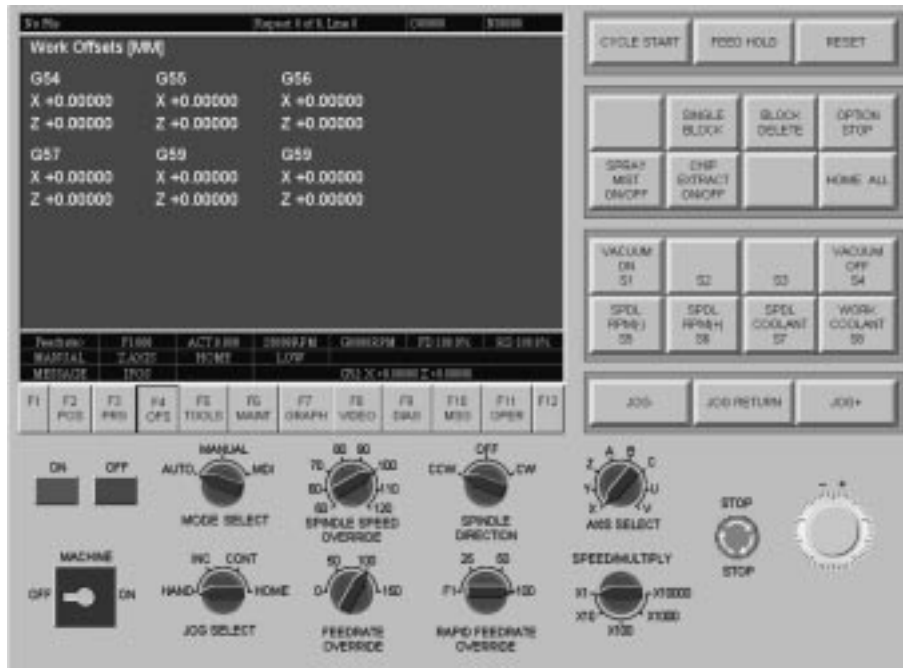


Fig. 3. Control panel of the virtual machine.

The editing of NC program, the setting of cutting tools and work offsets can also be done via this control panel. The states of axis position of NC machine tool and settings are fed back to the control panel.

*Information module*

The information module is composed of two sub-module which are the data buffer and internal database. The data buffer is a dynamic database, which consists of the run-time data for real-time updating the scenarios of the virtual machine motions. Examples include the real-time coordinates of the position of the machine slides and spindle, the change of the geometry and attributes

of the workpiece during machining, the status of the control panel buttons, etc. The internal database, on the other hand, composes of libraries of tool information, machine characteristics, workpiece information, materials, setup parameters of the machines, etc. The major difference between the data buffer and the internal database is that data in the data buffer are updated automatically by the interaction between the users and the virtual environment whereas the internal database contains the nominal data used in the training system.

*Event processing module*

As shown in Fig. 4, the event processing module is used to process the user's operations on the

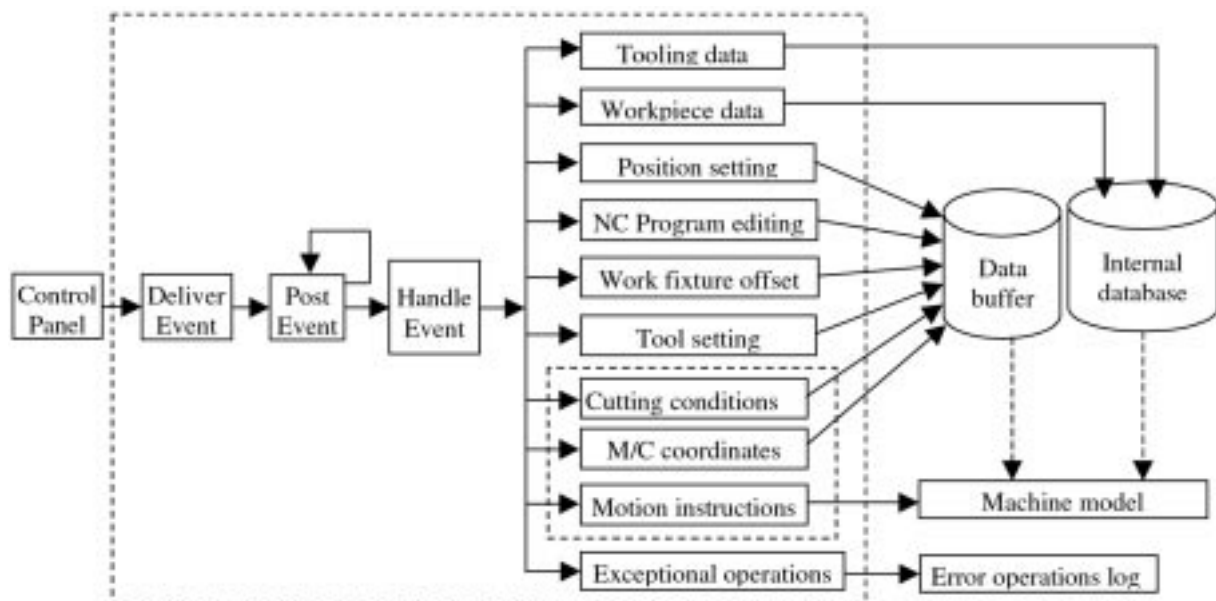


Fig. 4. Schematic diagram of the event processing module.

control console. Every user's operation on the control console can be processed as an event. When there is a user's operation on the control console, it will be delivered to the event processing module. Then the event processing module processes the event and the related message, and decides the sequence of the actions that would be carried out. The virtual objects will be called after the events are processed. Exceptional operations are treated as error operations. The rest of operations, such as tool offset setting, work offset setting, the editing of NC program, etc., are processed and the related information are stored in the information module.

#### *Virtual objects*

The VTW is basically made up of two major virtual objects which are the virtual ultra-precision machine for performing single-point diamond turning process as well as the virtual inspection machine for surface metrology. The virtual ultra-precision machine is designed based on the specifications of a Nanoform 300 two-axis CNC ultra-precision machine from Taylor Hobson Pneumo Co. In the virtual ultra-precision machine, the thermal model, kinematic model and the dynamic model [5] are used to simulate the error motions caused by the thermal effects, the kinematic and dynamic characteristics of the machine, respectively. The machine's actual behavior resulting from the various error motions and the change in work material properties are simulated by an error generation model [3], a workpiece model and a cutting model [6, 7]. Hence, the surface topography of the workpiece is simulated by a surface topography model [8]. The virtual machine is also designed for compensating the form errors based on a residual form error compensation model [9].

For the virtual inspection machine, the form and surface roughness measurements are accomplished by a metrology model, which simulates the working principle of a Form Talysurf machine. Similar to the virtual ultra-precision machine, the virtual inspection machine is incorporated with its kinematic and error generation models for the simulation of the measurement process. The Form Talysurf machine is a touch probe instrument which captures the surface data by a diamond stylus. The data analysis starts with removing the trend in the sampled data based on the nominal optical parameter input prior to the measurement. The modified surface profile can be either used to determine the form error of the surface or to compensate the tool path. With the use of different roughness/waviness filters and cut-off length, the surface roughness profile and the waviness of the surface can be predicted and simulated [10].

#### *Virtual environment simulator*

The main function of the virtual environment simulator is to create immersed computer-simulated environment that mimics real-world scenarios to facilitate learning of cognitive and

physical skills. The representation of 3D object geometry is an important step in the graphical simulation of reality, since it describes the real objects and provides the required data for the realistic simulation of the original entities and their behaviors. The geometric modeling and its related representation schemes are already well studied [11–13]: wire frame, surface, constructive solid geometry (CSG), manifold and non-manifold boundary representation (B\_Rep). Each of these representations has pros and cons that characterize and enable them to be used in a specific application context such as product modeling, virtual environments, etc.

#### *Selection of virtual reality system (VRS)*

Virtual reality (VR) can be described as the science of integrating human with information [14]. It consists of three-dimensional, interactive and computer generated environment. A VR model differs from that produced by a CAD system in two basic ways. Firstly, the objects, some of which represent the users, can interact. Secondly, behaviors can be associated with objects. The model itself may represent a system in the real world and can be effected by that system through control and monitoring devices (e.g. control console).

Generally, a virtual reality system (VRS) can be classified into two main types which are immersion VRS and Desktop VRS, respectively. For the immersion VRS, the user is surrounded by the virtual environment. The user can hear, visualize and interact with the artificial environment as if he situates in a real world. The user can fully immerse in the virtual environment, interact with the virtual device and get a good sense of realistic participation. However, the device investment is quite expensive. To build such a system, a considerable amount of hardware is needed such as a powerfully graphical workstation, a head-mounted display (HMD) and data glove, etc. The Desktop VRS, on the other hand, is displayed to the user on a conventional computer monitor. 3D perspective display technique is used to project 3D objects onto a 2D plane, says the computer screen. This system is more economical, only low cost device is needed, such as a mouse or a space ball, a stereo display monitor and stereo glasses, etc. The major advantage of Desktop VRS over Immersion VRS is the cost. This offers an extremely attractive solution for many applications. In the present study, the Desktop VRS is selected for the development of the training system.

#### *Modeling of the virtual objects*

The model of a virtual object can be created according to the specifications of real device such as structure, geometric dimension, etc., including the behavior definition of the device. Object-oriented modeling is an effective approach to define geometric models with high modularity [15]. Figure 5 shows the schematic diagram of the

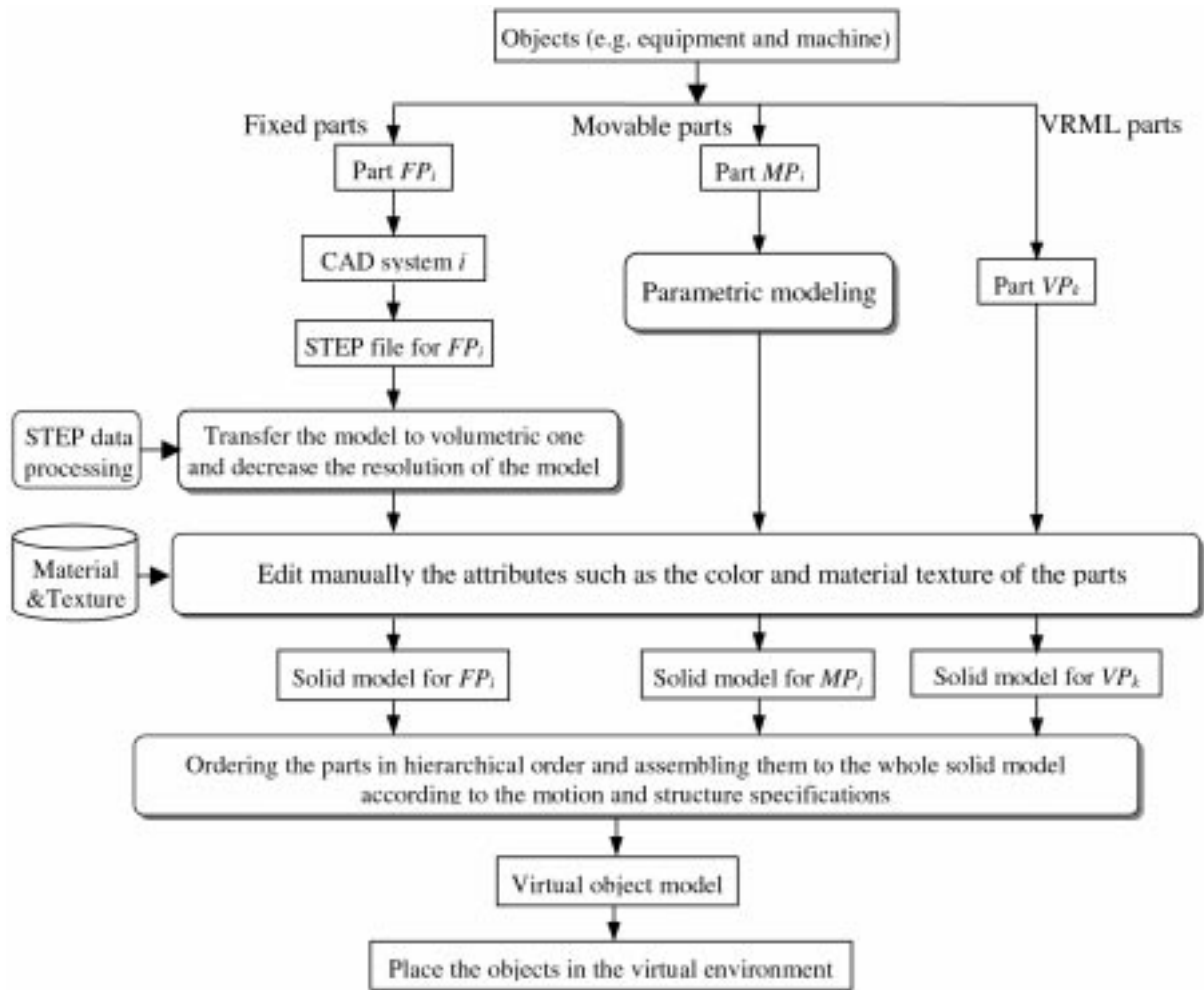


Fig. 5. Schematic diagram for the virtual object generation.



Fig. 6. Nanoform 300 ultra-precision machine.

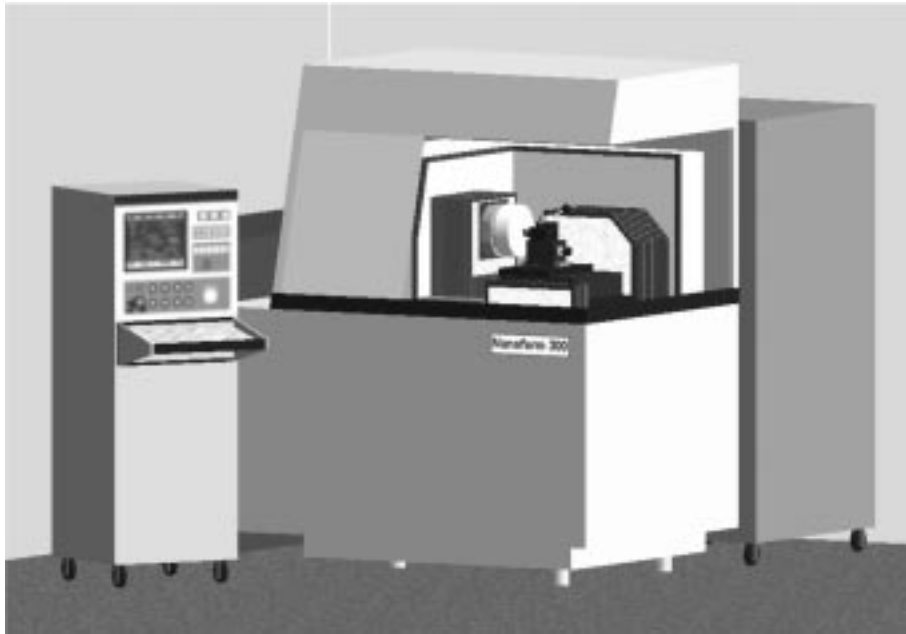


Fig. 7. Solid model of the virtual Nanoform 300 ultra-precision machine.

virtual object generation in the VTW. Basically, the modeling of a virtual object starts with the classification of the parts composing the object into fixed, movable and VRML parts, respectively. For fixed parts, the geometric model of individual part is built by CAD software (e.g. Pro/Engineer, AutoCAD, etc.). The STEP standard file output from the CAD software will be transferred into volume model and its resolution has to be reduced. Hence, the attributes such as color, materials and texture are added to the volume model. For movable parts, the parametric modeling techniques are used to build the volume model of individual movable part. VRML parts are those standard parts which are available from commercial software packages. These three types of part models are ordered hierarchically and assembled to a complete solid model of the virtual object which will be put into a virtual environment for subsequent manipulation. Figures 6 and 7 show a comparison between the real and virtual representation of the Nanoform 300 ultra-precision machine while that for the Form Talysurf machine are shown in Fig. 8 and 9, respectively.

Once the construction of the virtual objects for the VTW is completed, these objects are integrated into the virtual environment using the OpenGL software. A scene of the virtual environment created for the VTW is shown in Fig. 10. The virtual environment is designed and built based on the Ultra-precision Machining Centre of The Hong Kong Polytechnic University. Basically, the VTW consists of two virtual laboratories which are the virtual machining laboratory and the virtual inspection laboratory, respectively. The virtual machining laboratory is made up of the virtual Nanoform 300 ultra-precision machine and its accessories such as fixtures for the machining process whereas the virtual inspection laboratory

is made up of the virtual Form Talysurf machine and its accessories for the measurement of form and surface roughness of the diamond turned surface (Fig. 10).

#### IMPLEMENTATION ASPECTS OF THE VTW

##### *Technical aspects*

For the implementation of the VTW, Visual C++, Pro/Engineer and OpenGL were used for the development of the virtual environment. For modeling and pre-processing of the virtual objects, the relevant graphics supporting libraries of OpenGL were used which allow for the creation of object hierarchies, level of details, add color,



Fig. 8. Form Talysurf machine.

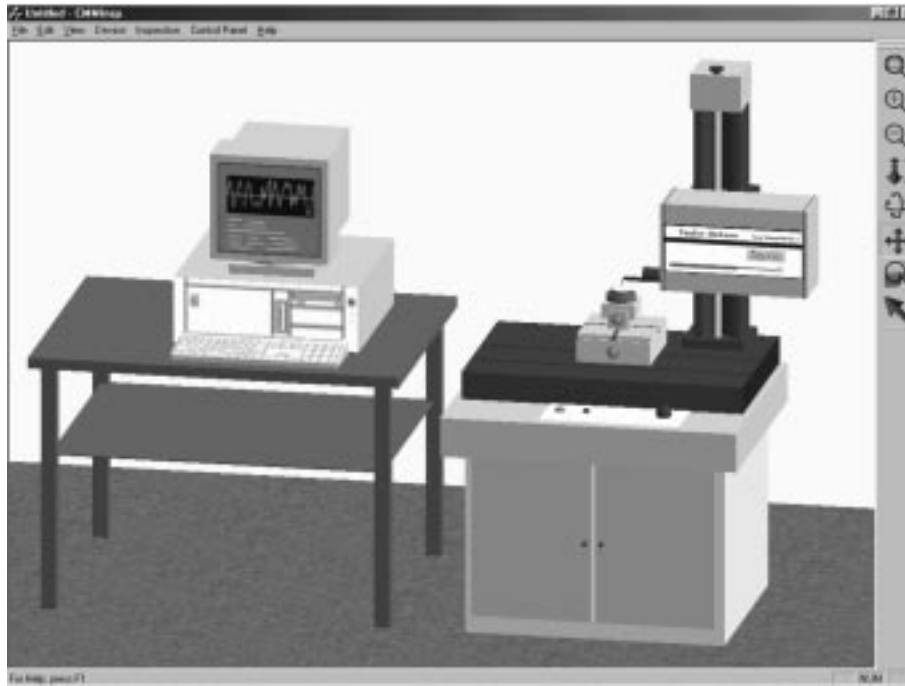


Fig. 9. Solid model of the virtual Form Talysurf machine.

material and texture of the objects. For the development of the interactive virtual environment, the OpenGL was also employed as the 'assembler' language for the graphic processing which possesses numerous functions available to create animation sequences, to link the solid model

objects and generally, to interact with the virtual objects of the scene. OpenGL provides the user with certain advantages for creating interactive applications. In the VTW, two computer monitors are connected to one computer, one is for the control console and the other is for the simulation.

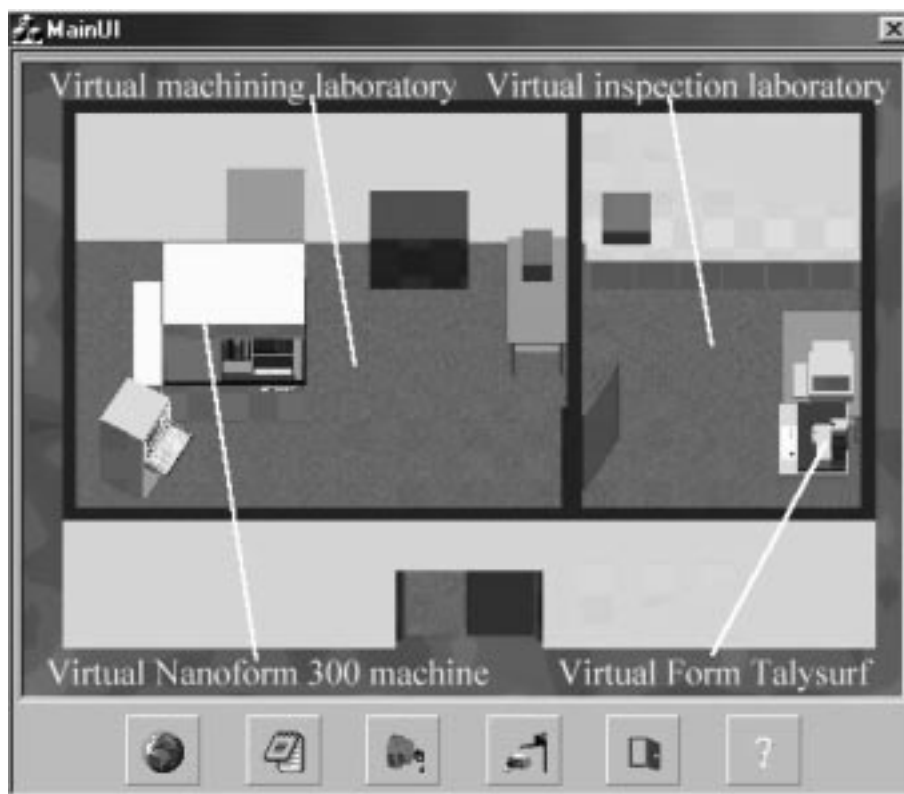


Fig. 10. Scene of the virtual environment of the VTW.

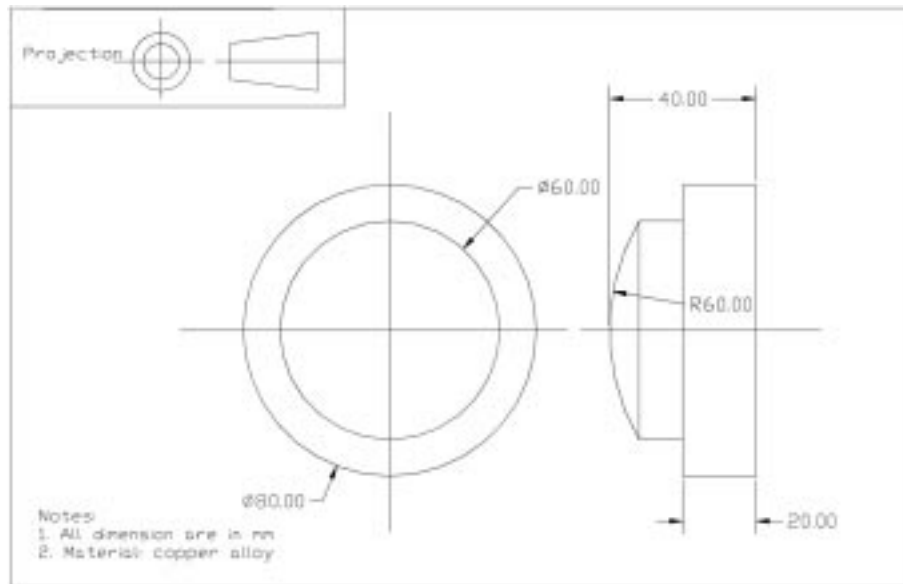


Fig. 11. Drawing of the the workpiece.

Control console monitor is used to issue control commands and NC programming. All operational messages are output from it. Simulation monitor is used to display the results of the control commands issued by the users.

#### *Training aspects*

The VTW will be incorporated in a two-hour VR training session for a M.Sc. subject named Advanced Manufacturing Technology. The subject is composed of two parts which include a classroom lecture and a laboratory exercise. As only one machine is available and the machine is

expansive, only trained technicians are authorized to operate the machine. The laboratory session is traditionally conducted in a demonstration manner. The students will not have the opportunity to conduct the cutting tests themselves and carry out the NC programming.

In the training session, the students will be expected to complete several tasks. The expected time for the completion of each task will be about 30 minutes. The tasks will be related to the machining of optical surfaces for products such as mould inserts and prototype lenses. The activities for the tasks include the control of the

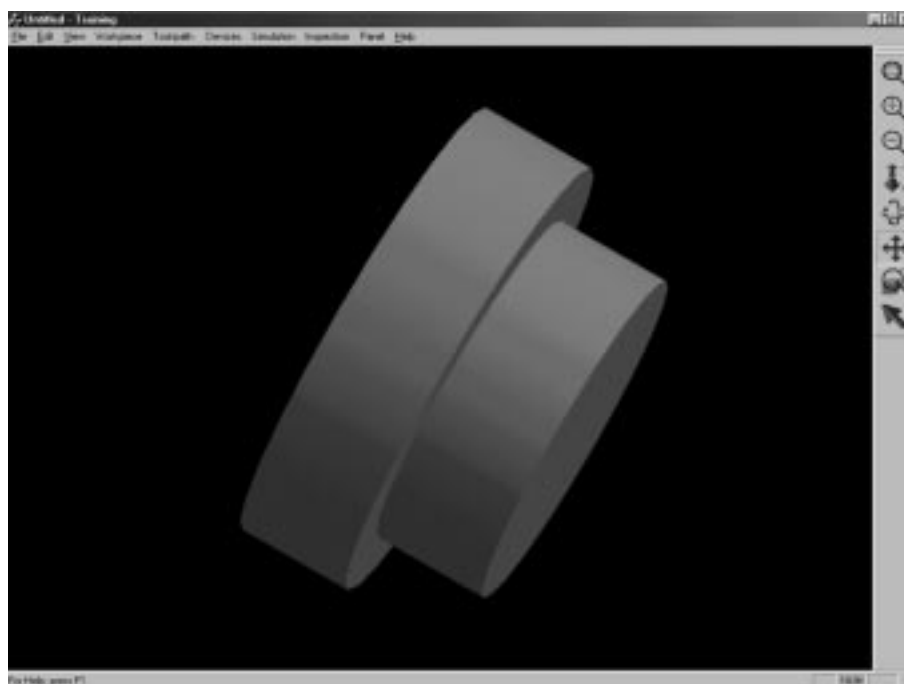


Fig. 12. Virtual work blank.



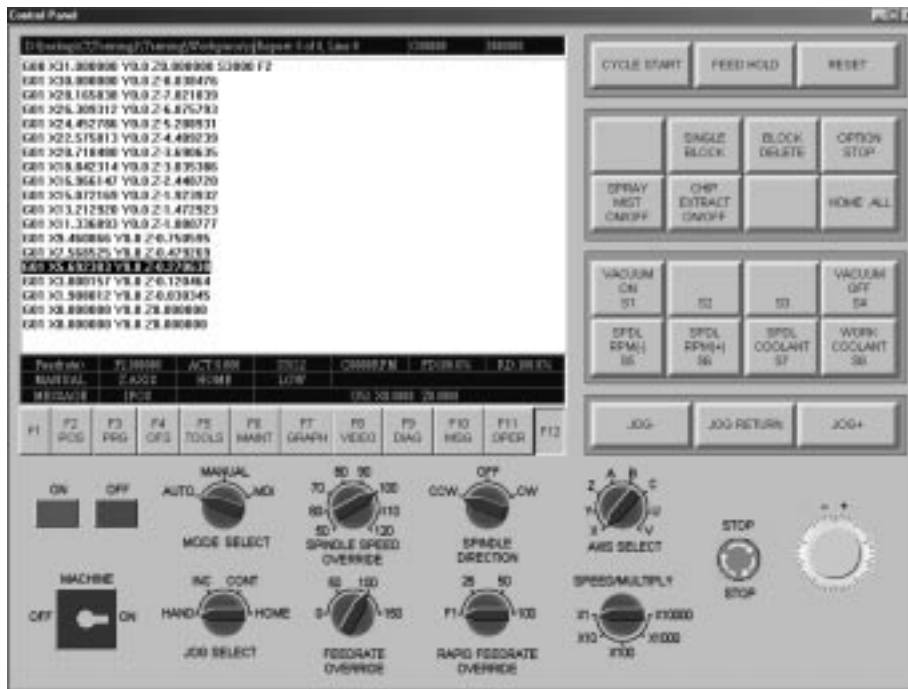


Fig. 13. Tool path programming.

machine, the selection of optimum cutting conditions, the programming of the NC tool path, the inspection of the surface quality of the workpiece and troubleshooting of the machining problems. For the assessment of the student performance, the VTW will record all the inputs by the students and these will be compared with the nominal inputs preinstalled in the VTW by well experience instructors. Hence, the learning outcome will be evaluated based on several components which include machine operation, control and troubleshooting.

Apart from the training of the tertiary students, the VTW will also be used for conducting training for machine operators.

### ILLUSTRATIONS OF THE TRAINING ACTIVITIES

To illustrate the functional capabilities of the VTW, a case study was prepared for the machining and inspection of a spherical mould insert as

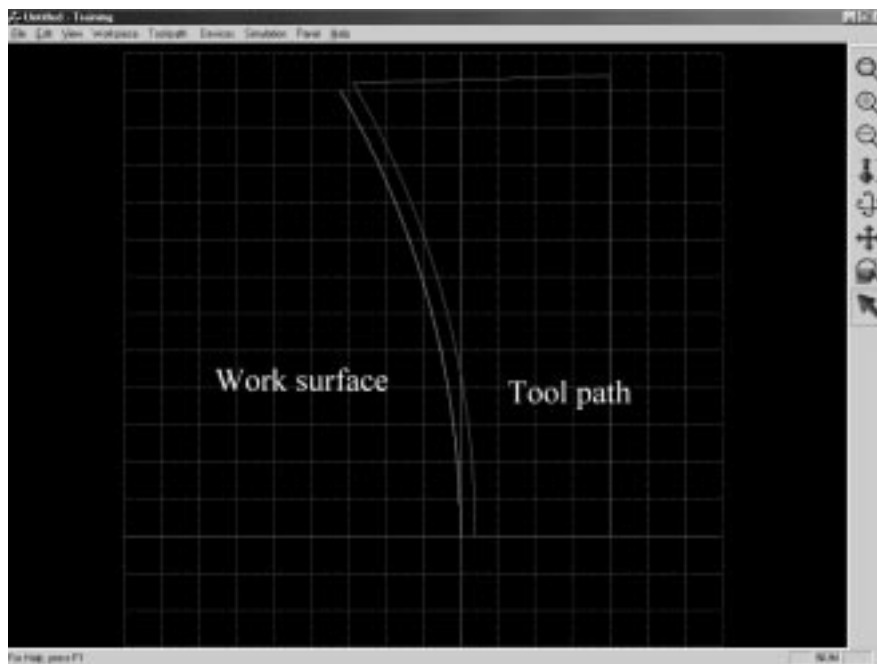


Fig. 14. Simulated tool path for the machining of the optical surface.

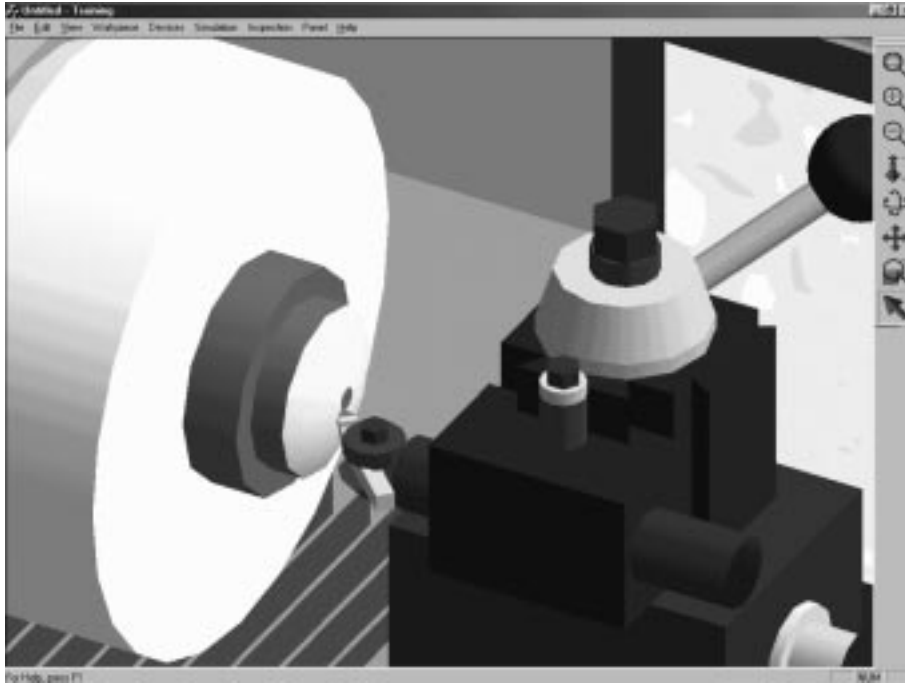


Fig. 15. Virtual machining of the optical surface.

shown in Fig. 11. Figure 12 shows a virtual work blank of a mould insert. The process of machining the insert started with the determination of the optimum cutting conditions. This is accomplished by a model-based simulation system [8] incorporated in the VTW. The optimal cutting conditions were selected based on the minimum surface roughness criterion. Then, the programming of the numerical control (NC) tool path was

conducted with the use of a tool path generator (TPG) software [9]. The TPG is a software package for the rapid construction of the NC programs for direct machining of the optical surfaces. Upon the input of the tool geometry and optical surface parameters as defined by the universal optics equation, TPG is capable of generating the TAP format file for machining the optical surfaces (Fig. 13). Figure 14 shows a simulated tool path

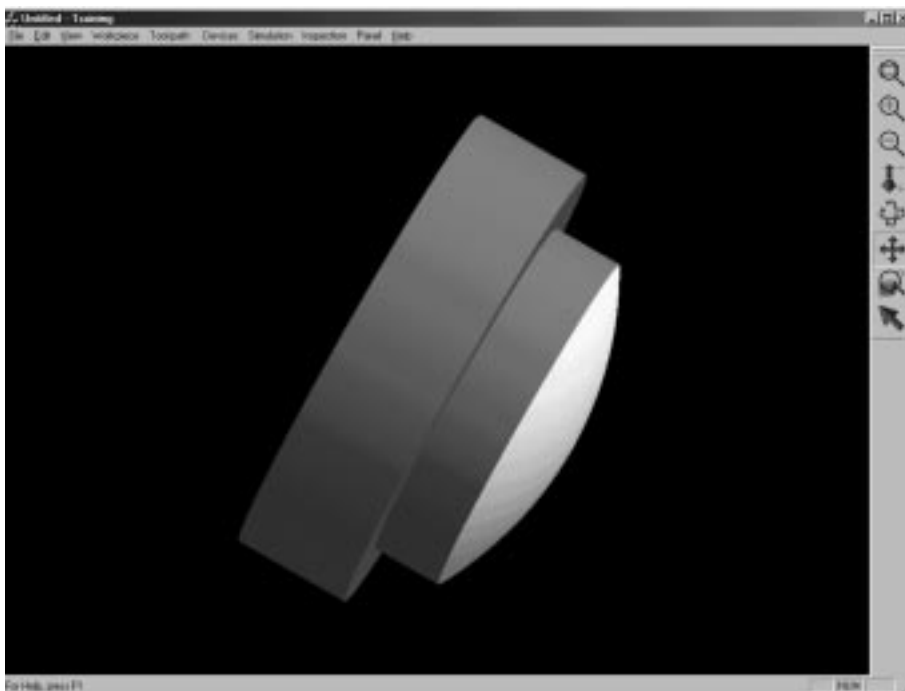


Fig. 16. Solid model of the machined workpiece.

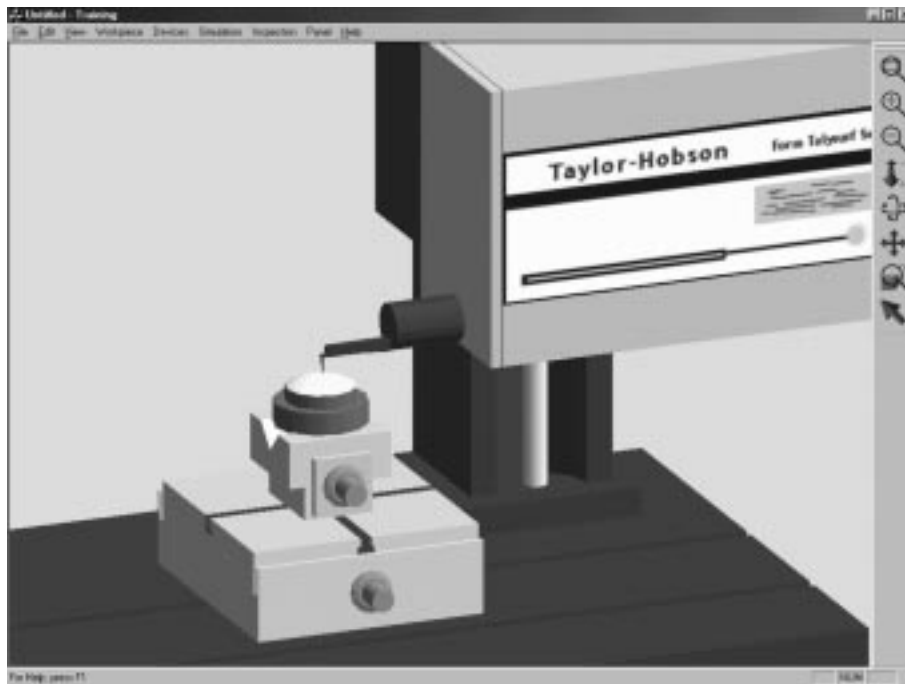


Fig. 17. Virtual inspection of the surface quality of the diamond turned workpiece.

for machining the mould insert. The user could make use of the NC program to conduct the diamond turning process (Fig. 15). Upon finishing the machining process, the VTW generated the 3-D solid model of the virtual mould insert as shown in Fig. 16. As shown in Fig. 17, the diamond turned mould insert was inspected by the virtual Form Talysurf machine. The results of measurement which include the roughness profile and the surface roughness parameters were displayed to the user as shown in Fig. 18.

## BENEFITS AND APPLICATION OF VTW

### *Benefits*

The development of the VTW offers a number of benefits as below:

1. VTW provides a unique exploring of experience not possible with a real machine, which helps better retain trainee's attention than conventional workshop training such as reading a manual.

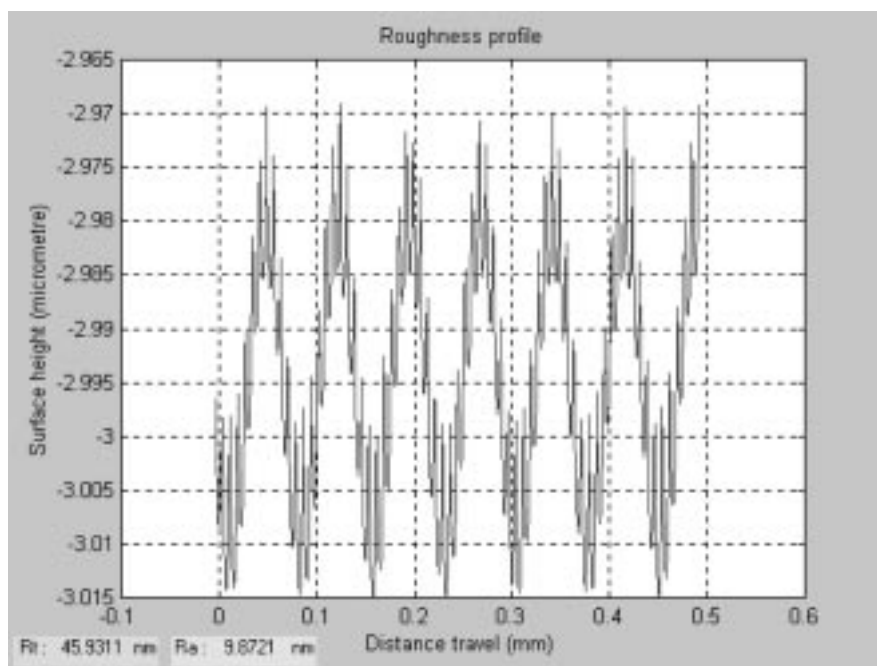


Fig. 18. Simulated result of surface roughness measurement.

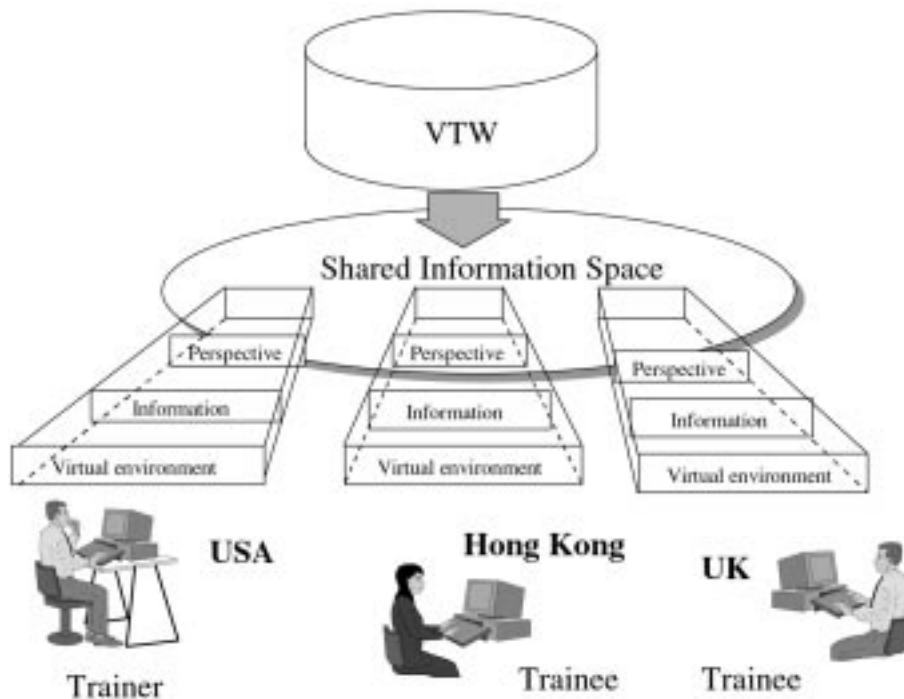


Fig. 19. A conceptual view of the DVTE.

2. The user or trainee can practice all necessary operations, procedures and skills in a safe environment, while maintaining a high degree of realism.
3. A reduction of the investment in training can be realized since various types of sophisticated and expensive machinery may be represented in a virtual environment.

#### *Other applications*

The physical co-location of experts and trainers for sharing their experiences and expertise in problem solving is no longer a trivial issue. This leads to many investigations of the adoption of distributed virtual environment (DVE) for supporting cross-border training activities.

High-speed networks, distributed virtual environment and multimedia communications are now commercially available and have a potential to support interaction between geographically dispersed users in a much more dynamic and synchronous nature than traditional file exchange and electronic mail [16]. Such advances have made it possible to further develop the proposed VTW to operate under distributed virtual training environment (DVTE) for geographically dispersed users to conduct training. Figure 19 depicts a proposed conceptual view of the DVTE. Under the DVTE, the trainee and the trainer have user interfaces that they may configure with the operations they wish to perform and the visualization style they wish to use. The operations will be performed on a shared information by a set of distributed applications

that are invoked and controlled in the background automatically by the DVE environment.

## CONCLUSIONS

The purpose of a training workshop for engineering personnel is to provide skills and know-how which are basic to acquire new skills. The future of training systems is destined to become an interactive process, as the trainee may participate in the learning experience actively and not passively. Both the academic institutions and the industry are now beginning to realize that VR has the potential to become a powerful technology for developing interactive training tools for skills and knowledge training.

This paper describes the current development of a virtual training workshop (VTW) for ultra-precision machining and inspection. The VTW provides an affordable and risk-free training environment for training engineering personnel on the use of expensive ultra-precision facilities. The development of the distributed virtual training environment for supporting cross-border training activities will also be the future research arena that would be explored.

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## REFERENCES

1. M. Iqbal and M. S. J. Hashmi, Application of virtual reality for the training of engineering personnel, *Proc. Int. Conf. Advances in Material and Processing Technologies, AMPT'99 and 16th Annual Conference of the Irish Manufacturing Committee, IMC 16*, (1999) pp. 1959–1965.
2. N. Ikawa, R. R. Donaldson, R. Komanduri, W. Knig, T. H. Aachen, P. A. McKeown, T. Moriwaki and I. F. Stowers, Ultra-precision metal cutting—the past, the present and the future, *Annals of the CIRP*, **40**(1) 1991, pp. 587–594.
3. C. F. Cheung and W. B. Lee, A framework of a virtual machining and inspection system for diamond turning of precision optics, *J. Materials Processing Technology*, **119**(1–3), 2001, pp. 27–40.
4. M. Weyrich and P. Drew, An interactive environment for virtual manufacturing: the virtual workbench, *Computers in Industry*, **38**(5–15), 1999.
5. W. B. Lee, C. F. Cheung and S. To, Materials induced vibration in ultra-precision machining, *J. Materials Processing Technology*, **89–90**, 1999, pp. 318–325).
6. W. B. Lee, Prediction of microcutting force variation in ultra-precision machining, *Precision Engineering*, **12**(1), 1990, pp. 25–28
7. W. B. Lee and M. Zhou, A theoretical analysis of the effect of crystallographic orientation on chip formation in micro-machining, *Int. J. Machine Tools and Manufacture*, **33**(3), 1993, pp. 439–447.
8. C. F. Cheung and W. B. Lee, Modeling and simulation of surface topography in ultra-precision diamond turning, *Proc. Inst. Mechanical Engineers Part B, J. Engineering Manufacture*, **214**(6), 2000, pp. 463–480.
9. W. B. Lee, C. F. Cheung, W. M. Chiu and T. P. Leung, An investigation of residual form error compensation in the ultra-precision machining of aspheric surfaces, *J. Materials Processing Technology*, **99**(1–3), 2000, pp. 129–134.
10. C. F. Cheung and W. B. Lee, A theoretical and experimental investigation of surface roughness formation in ultra-precision diamond turning, *Int. J. Machine Tools and Manufacture*, **40**(7), (2000) pp. 979–1002.
11. A. Baer, C. Eastman and M. Henrion, Geometric modeling: a survey, *Computer Aided Design*, **11** (5), (1979) pp. 253–272.
12. A. Requicha, Representations for rigid solids: theory, methods, and systems, *ACM Computer Surveys*, **12**(4), 1980, pp. 437–464.
13. K. J. Weiler, Topological Structures for Geometric Modeling, Ph.D. thesis, Rensselaer Polytechnic Institute, Troy, New York (1986).
14. K. Warwick, J. Gray and D. Roberts, *Virtual Reality in Engineering*, The Institution of Electrical Engineers, London (1993).
15. P. Ball and D. Love, Expanding the capabilities of manufacturing simulators through application of object-oriented principles, *J. Manufacturing Systems*, **13**(6), 1994, pp. 412–423.
16. J. H. Maxfield, L. T. P. Fernando and P. M. Dew, Supporting multidisciplinary teams in concurrent engineering, *Virtual Prototyping-Virtual Environments and Product Design Process*, Chapman & Hall, (1995) pp. 160–172.

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