ABSTRACT

Operations and maintenance work on the China Light & Power transmission system currently require skilled engineering staff, with a minimum of three years training, to ensure that switching, isolation and earthing are properly executed before issuing safety documentation to tradesman for work on the released equipment.

Business process re-engineering work identified significant productivity gains could be achieved by enabling the tradesmen to also carry out the switching and documentation duties themselves, but the training required to achieve this goal is a formidable challenge.

This paper describes the development of an innovative training simulator, utilizing the benefits of virtual reality, digitized video, and interactive CD-ROM, to create the appropriate operational environment and allow simulation of critical switchgear operations without the restrictions of other training methods.

Experiences gained in developing concepts and meeting considerable software challenges are outlined, and the potential of the simulator for future operations training discussed.

1.0 INTRODUCTION

The China Light & Power (CLP) transmission system operates at 400kV and 132kV, providing power to bulk supply points for onward distribution to over 1.6 million customers.

The extremely high load density in Hong Kong, and shortage of land, has resulted in an extensive cable and overhead line system with a heavy reliance on gas insulated switchgear (GIS). With more than 1300 bays of GIS installed in 127 transmission substations, there is considerable daily system activity in switching, isolating, issuing permits to work, and related activities. Over 2,000 safety documents are issued each year for maintenance work, fault repairs, and new equipment commissioning.

Operations and maintenance tasks on the CLP high voltage transmission system are performed by skilled engineering staff who are experienced in all aspects of switchgear and equipment functionality. However, due to the large range of designs and manufacturers of such equipment installed on the network, it takes approximately three years before staff are fully trained and authorized to carry out such duties.

Since maintenance or repair work can only commence after issuance of a safety document, time was frequently lost between the tradesmen arriving at site ready to start work and the issuance of a permit to work. With an average of 30 such situations occurring each day, CLP recognized that considerable productivity gains could be achieved if the tradesmen were able to perform the switching tasks
themselves. The training necessary to achieve this goal, however, would present major challenges, with language, formal education, and culture representing the main barriers.

In order to achieve this objective, it was clear that innovative educational methods would be necessary to train a large group of tradesmen with formal qualifications and experience very different to that of existing engineering staff.

One possible way forward demanded evaluation of the benefits offered by virtual reality (VR), such that operator trainees could view and perform switching tasks on exact visual images of switchgear without all the difficulties of conducting this training inside a working substation. Hence, we conceived the notion of a switchgear operation simulator. With VR technology approaching maturity, the potential benefits it offered in operator training persuaded CLP to pursue further development in collaboration with the Chinese University of Hong Kong (CUHK).

This paper describes the development of VR techniques for switchgear simulation, the relationship of VR to other training methods, and VR’s potential for extended use in operational work.

2.0 CREATING THE TRAINING MATERIAL

This project relied on a variety of hardware and software technologies. Our goal was to simulate as much of the operation as possible using VR. However, digitized video, hyper-text markup language (HTML), and interactive CD-ROM also became important components of the training system.

2.1 Preparation of the Training Scenario

The pilot project for this simulation effort is a switching procedure for one of six 240MVA transformers in the Tsz Wan Shan substation, in Kowloon, Hong Kong. It transforms from the grid of 400,000 volts down to 132,000 volts, and is controlled and protected by GIS switchgear on both sides. The scenario begins with phoning an engineer at the control center for instructions, and proceeds through physically operating the isolators, earthing switches, and other controls until isolation and earthing is complete.

As a first step toward developing the training materials, CLP personnel escorted CUHK researchers on a tour of the facility, walking through the scenario and explaining the operation of the many knobs, switches, indicators, and alarms. In addition, CLP provided a written outline of the procedure and drawings of the equipment, and the CUHK team took photographs and notes of their own.

An immediate benefit of this collaboration was that it documented a procedure which previously had resided exclusively in the minds of skilled engineering staff. The exercise of setting it down in writing forced the participants to explicitly consider every step. As a result, the procedure itself went through several modifications.

Early in the project, it was arranged to videotape the procedure, both for our own reference as well as to serve as raw material for the final training package. The first taping session revealed various difficulties not previously identified. Providing adequate lighting and camera angles in tight situations added to the complexity of the operation, and the “star” engineer performing the switching found it necessary to modify his motions accordingly. A second and final taping session resolved these issues. Besides forming an important part of the final package, the video proved to be a valuable reference for the CUHK team, who referred to it often in developing the virtual reality simulations.

2.2 Hardware for Virtual Reality

“Virtual reality” is loosely defined. In general, it implies (at least) stereoscopic perspective projection to enhance the sense of visual depth, coupled with three-dimensional interaction. This depends on projecting separate, slightly different perspective views for the left and right
eyes. How these views are separated and presented depends on the type of display. For this project, we used a desktop system, shown in Figure 1, consisting of the following elements:

- a computer workstation that can display field-sequential stereo perspective images at 120 frames per second (left eye, right eye, left eye, right eye …);
- a set of stereo glasses, with liquid-crystal shuttered lenses, synchronized with the computer display by an infrared emitter, and equipped for ultrasound position tracking;
- an ultrasound 3D mouse and position-tracking system (which tracks the mouse and stereo glasses simultaneously).

![Figure 1: Hardware Configuration for Desktop Virtual Reality](image)

There are several advantages to this over a head-mounted system:

- The resolution is higher than in most head-mounted displays. In width, it’s the full resolution of the normal computer display; in height, it’s half of the normal resolution in order to achieve twice the frame rate, for a flickerless field-sequential display. By comparison, affordable head-mounted displays are limited by significantly lower resolution. According to an article in Scientific American [1], “most affordable headsets render you legally blind … you can’t make out the big E on an eye chart at a virtual 20 feet.”

- The view is “public”: colleagues can see what the user sees. Even without the stereo glasses, though they see a double image, the parallax is generally small and the image is intelligible. With another set of eye wear, an observer can share the stereo view with the primary user, at relatively little additional cost. This is particularly relevant for a training application.

- Because the system uses the normal computer display, the eye wear is simpler, lighter, and less expensive than head-mounted displays.
There are also disadvantages:

- The virtual world is limited to the frustum defined by the user’s eyes and the stationary display. Some refer to this as “fish tank” virtual reality. By comparison, head-mounted displays provide an unlimited field of view.

- The left and right images share the same physical display, and visual separation may be imperfect. By comparison, head-mounted systems provide perfect separation of the left and right images on separate physical displays.

For this project, the advantages of a desk-mounted system outweighed the disadvantages, particularly with regard to cost and technical risk. The desk-mounted system allowed us to develop the training application with existing computer workstations, and required only an incremental investment in stereo glasses and a three-dimensional input device.

2.3 Software for Virtual Reality

A significant feature of this VR system, as compared to a head-mounted system, is that the user is not blinded to the real world. In particular, his real hands and 3D mouse remain visible in conjunction with the ghostly stereo image of the virtual world. For intuitive interaction with the virtual world, the mouse’s effective position should agree with its visible position. While this may be obvious, it is not automatic. The spatial alignment between the physical and virtual worlds must be explicitly computed by the software.

The position-tracking hardware provides coordinates relative to the ultrasound transmitter, but the transmitter’s position relative to the display screen and the virtual world is arbitrary. Neither the hardware, nor the minimal software that comes with it, provide any mechanism for attaching the tracker’s coordinate system to the virtual world.

To coordinate the physical and virtual worlds, it was necessary to improvise a stable mount for the transmitter, and to develop position-tracking software to calibrate and compensate for its offset relative to the screen.

Resting on top of this infrastructure are the switchgear simulations themselves. These depend on the definition of generic interactive objects that can be instantiated with different values and assembled in different configurations to simulate various devices.

For example, all doors have a geometry, a location, a hinge side (left or right), a swing direction (clockwise or anticlockwise), and a maximum open swing. A typical example of this can be seen in Figure 2. The behavior of the generic door object is programmed in terms of these attributes. To add an instance of a door to an assembly, it’s necessary only to assign specific values to these attributes. The methods (programmed functions) of all doors are the same; only the instance variables change.

To create an extensible VR environment for switchgear simulation, it’s crucial to identify the set of interactive objects – doors, switches, knobs, locks, gauges, and so on – and distinguish their essential common behaviors from their instance variables. For greatest programming efficiency, commonalities should be exploited where ever possible. For example, doors and switches may both be derived from an abstract class of “things that swing around an axis”.

For 3D scene modeling, we’re using a commercial object-oriented software-development system [2,3,4]. The development kit includes built-in support for stereo viewing. Unfortunately, as will be discussed later, the algorithm it uses for stereo perspective projection is imperfect.
2.4 Hand-Eye Coordination and Depth Perception in Virtual Reality

To simulate a hands-on training experience, it’s important that the VR environment provide good hand-eye coordination.

Discrepancy, especially in depth perception, arises from the following sources:

- The screen is not planar, though the mathematics of perspective projection assume that it is.
- The calibration of the tracking system relative to the screen is imperfect. This is due in part to the curvature of the screen, and also to the thickness of the glass in front of the actual display surface.
- The modeling system’s algorithm for stereo projection is imperfect. It assumes a rotation between the left and right views that places each eye at the center of its own projection plane. The correct algorithm translates the eyes across a single common projection plane while maintaining parallel projection axes [5].

Despite these sources of error, we have been able to keep the visual discrepancy between the virtual cursor and the physical mouse within a range of 1 to 3 centimeters, approximately. The discrepancy is least at the center, and greatest at the periphery. The biggest variable is the care with which the user calibrates the tracking system to the screen.

We plan to override the default stereo algorithm (based on rotation) with our own algorithm (based on a translation) in the next phase of this project. We believe that this may eliminate much of the visual discrepancy.
As mentioned above in section 2.2 on hardware, the separation of the left and right images in desktop stereo is imperfect, due the persistence of the screen phosphors – especially the green – and the incomplete opacity of the liquid crystal shutters in their “closed” state. This also interferes slightly with depth perception. It can be alleviated by avoiding the use of bright green and by keeping fresh batteries in the eye wear.

There is also a discrepancy between binocular convergence and optical focus. Whilst the eyes rotate to converge on points projected to different depths, they must continue to focus on the physical screen where the optical images actually exist. This is unnatural, and seems to require a period of acclimation for each individual user. Some users seem to adapt quicker than others. In general, an application can minimize the discrepancy by centering the stereo depth of the model at the screen plane. At the same time, in order to touch a point in the virtual model with the physical 3D mouse, the point must be projected to appear in front of the screen.

2.5 Zooming and Scaling in Stereo

In our simulation project, we have encountered problems in trying to interact with a small image of a large piece of equipment: the knobs, switches, and so on are almost too small to resolve, let alone control. Simply moving the virtual camera closer does not solve the problem. Though it enlarges the image, it also pulls it away from the screen and toward the user. The result still appears as a small three-dimensional object, but now uncomfortably close to the user’s face.

To zoom-in on the virtual model, the stereo offset of the virtual camera must be scaled in proportion to its distance from the virtual model. This, in effect, grows the model relative to the user, or shrinks the user relative to the model. The end result is that the model’s image increases in size while maintaining its stereo depth at a comfortable distance, near the screen.

Our 3D mouse software assigns different functions to the various buttons, allowing the user to control three-dimensional pan and zoom independently, to maintain a comfortable size and proximity of the projected virtual model.

2.6 Complexity of Interaction Versus Simplicity of Device

The 3D mouse is considerably simpler than a human hand. Virtual reality renders the user not only legally blind, but crippled as well. Interaction that requires two-handed dexterity – such as removing a padlock from a door latch – is not easy to simulate with a single unbending pointer and three buttons. While we could invent a complex series of twisting, turning, and pulling motions to simulate some activity, it would require considerable programming for an interface that, ultimately, nobody would know how to use. If the purpose of the software is to train people to operate real equipment, it’s essential that training not be required to use the software. Otherwise, the software itself becomes the object of the training, and the original application remains unfulfilled.

It’s our hypothesis that, for an intuitive interface, the complexity of motion required to accomplish a task with a simple 3D mouse should be limited to translation in a single plane or rotation about a single axis. Furthermore, picking the object to interact with should depend only on the mouse’s position, and not its orientation.

In our application, the user picks a virtual door, switch, or knob by touching its image with the 3D cursor and pressing a mouse button. He opens a virtual door by translating the mouse in the x-z plane. The door interface computes the yaw of the door from the x-z location of the cursor relative to the hinge. Similarly, the user flips a switch by translating in the y-z plane. He turns a knob by rotating the mouse around the z axis.

The knob is an exception, in that z-axis translation is sometimes necessary along with z-axis rotation. This is a feature of the actual knob that we’re trying to simulate: it cannot be turned
into its full-clockwise or full-anticlockwise positions unless it is first pushed in. The real knob is spring loaded, and tactile feedback tells one how far to push before turning. In the VR simulation, the user can see that he is pushing the knob in, but he does not feel when it has bottomed out so that turning is allowed. It is unable to provide tactile feedback to prevent him from turning the mouse prematurely; we can only ignore the turn until the push is sufficient. This variable response to one degree of freedom (z rotation) based on an independent degree of freedom (z translation) is somewhat clumsy; the interface feels slightly unresponsive at times. Thus far, this knob is the most complex control we have simulated. Even here, all control motions – both the translation and the rotation – are relative to a single axis (z).

2.7 Production of Bilingual CD-ROM

Whilst the VR developments described in the previous sections made a very successful contribution to the training objectives of the project, there was strong agreement within the team that a CD-ROM containing all the annotated video sequences of the outage would provide a powerful learning medium for the operator and would allow integration of the VR sequences into the programme.

As discussed in section 2.1, the digitized video provides the trainee with a factual, sequenced visual display of all the steps necessary in isolating and earthing the 240MVA transformer in question. This digitized video approach offers specific advantages, some of which are outlined below:

- The system is portable and can be run on most PCs.
- Actual video sequences reinforce operator learning.
- Sequences can be replayed at any time.
- Appropriate interlocks and logic can be built into the sequences.
- The system provides self-paced learning outside the operational environment.

A typical screen display of the CD-ROM is shown in Figure 3 from which the operator can select the Cantonese or English version before clicking on the desired icon to see the complete video sequence.

![Figure 3: Bilingual Interactive CD-ROM](image)

### 3.0 RESULTS

The final training package consists of HTML and CD-ROM pages, digitized bilingual video clips, and virtual-reality simulations of key equipment. The “home page”, in both HTML and CD-ROM, is a flow chart showing the sequence of operations. Each box on the chart is illustrated with the first frame of the corresponding video clip. Clicking on the box plays the video. In the on-line HTML version, an adjacent button links to the corresponding VR simulation for each step.
With this system, the trainee can immediately see the entire sequence of actions, as well as focus on the details of particular steps as necessary. He can jump to a particular video clip, play it in stop action, study the captions and subtitles, then click a button to enter the virtual reality simulation and practice the operation himself.

4.0 DISCUSSION

Whilst the main driver in this project was enabling staff to achieve future productivity gains, the key to achieving this goal was a radical change in operations training, of which the switchgear operation simulator was a key component.

It soon became apparent that to simulate every action in the scenario by virtual reality was not a feasible option mainly because of the time required to achieve this. On the other hand, site experience demanded that training in certain critical actions, such as isolator operation, lock pin management, and earthing switch operation, should involve the operator in a kinesthetic as well as visual sense. Hence, these key functions were developed in VR. Many other aspects of work and their strict sequence, such as panel switching, lock management, and handling of alarms, were successfully implemented in HTML and interactive CD-ROM, incorporating digitized video clips and running in a computer windows environment.

This powerful combination of sequencing through the windows screens, allowing the operator to select and replay as necessary the exact switching steps, then entering into the VR environment to execute critical functions, has proven extremely successful – particularly since all steps are dubbed in both Cantonese and English.

Whilst the simulator appears to have successfully addressed the selected scenario, there are of course many hundreds of switching combinations involving different circuits and different manufacturers’ equipment. Hence, the ability of the system to reflect these many alternatives becomes an important issue. In other words, the simulator’s use will be mostly academic if it cannot reproduce conditions for the complete transmission system. This problem can be overcome:

- by developing a robust kit of generic objects in the VR environment – doors, switches, knobs, locks, and so on – that implement the essential actions of these devices, and that can be assembled in various configurations to simulate a variety of equipment with a minimum of additional programming;

- by developing video editing techniques that permit replacement of labels, names, and other specifics for similar switching sequences, and the overlaying of new video sequences where necessary.

When considered in its entirety, the combination of VR, HTML, and interactive CD-ROM has produced a training simulator that meets the demands specified at the outset of the project and is now currently undergoing evaluation by transmission operational staff.

5.0 CONCLUSIONS

Through a careful, step-by-step review of the switchgear operation, we identified certain critical procedures for which VR offered the best training medium, whilst for the overall sequence of steps, interactive HTML and CD-ROM incorporating digitized video, dubbed in Cantonese or English, proved most successful.

We conclude that the simulator is successful in satisfying the requirements defined by CLP at the commencement of the project. The application of this technology to other types of operational training, such as detailed maintenance, fault repairs, and contingency planning, offers terrific potential for the future.
6.0 ACKNOWLEDGEMENTS

The authors wish to thank the China Light & Power Co. Ltd., and the Chinese University of Hong Kong, for their generous support of this project.

At CUHK, in the Information Technology Services Unit, Augustine Lo organized the recording and digitizing of the original documentary video, which served as both a reference and raw material in developing the training materials. In the Department of Architecture, Benny Chow was indispensable in editing the video clips, authoring HTML documents, and producing the final CD-ROM. Albert Chan and Matthew Cheng produced the geometric models of the switchgear, working from technical drawings provided by CLP. From the Department of Computer Science, Chris Lo and Loren Chu assisted in software development.

7.0 REFERENCES


8.0 BIOGRAPHIES

Mr. Brown was born in 1948. He obtained his Honours degree and Masters degree from Heriot Watt University in Edinburgh, Scotland. He spent 12 years in the power industry with Scottish Power before joining China Light and Power Co. in 1981. During the past 15 years he has been involved with most of the technical and managerial issues associated with running the transmission system and is currently Chief Engineer of the Network Operation Department.

Mr. Lai was born in 1955. He began his career in the power industry with Hongkong Electric in 1977. In 1979 he joined China Light and Power as an engineer in the Transmission Department. In 1989 he worked as a First Engineer in the Transmission Circuits Branch of the Network Operations Department and was in charge of operation and maintenance activities on overhead transmission lines and underground cables of voltage from 66kV to 400kV. His major working experience is in operation and maintenance of transmission overhead lines.

Tsou Jin Yeu was born in 1959. He studied architecture at the University of Michigan, USA, earning his Master’s degree in 1986 and his Doctorate in 1992. After completing his studies, he accepted an academic appointment at the Chinese University of Hong Kong. He is now the Director of the Architectural Computing Laboratory and an Associate Professor of Architecture, teaching the integration of computing in architectural design.

Theodore W. Hall was born in 1957. In 1981, after receiving his Master’s degree in Architecture (with honors) from the University of Michigan, USA, he began his career as a software developer at the university’s Architecture and Planning Research Laboratory. In 1994, he completed his Doctorate in Architecture at Michigan, with a dissertation on “The Architecture of Artificial-Gravity Environments for Long-Duration Space Habitation.” Since then, he has been a postdoctoral fellow at the Chinese University of Hong Kong, specializing in software development for computer-aided architectural design.