Virtual Reality Research at TNO-FEL

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SUMMARY

Virtual environment (VE) technology is expected to make a big impact on future training and simulation systems. Direct stimulation of human senses (eyesight, auditory, tactile) and new paradigms for user input will improve the realism of simulations and thereby the effectiveness of training and simulation systems. After briefly summarising earlier work done at TNO-FEL, a definition of virtual environment simulations is proposed, along with a classification of various types of VE systems. This classification then proves helpful in assessing the applicability of VE technology to trainers and simulators. Next, a prototype system for training EVA procedures is described. Finally, the conclusions from this work are drawn, and directions for future research and development activities at TNO-FEL are given.

Keywords: virtual reality, human interface technology, simulators, trainers, real-time graphics, parallel processing

1 INTRODUCTION

1.1 Virtual environments: new technology for trainers and simulators?

Considering the recent developments in simulator technology, the last two years have been marked by a rapidly growing interest for virtual environment (VE) technology, also known as 'virtual reality'. Although many publications have been done on this subject, it is still veiled in wild fantasies and few people know the current possibilities and impossibilities. In this paper, we intend to discuss the applicability of this technology for trainers and simulators.

1.2 Outline of the paper

The paper gives an overview of virtual environment technology and its role in our research program concerning trainers and simulators. To this end, we first describe in section 2 related work that is done by the TNO Physics and Electronics Laboratory (TNO-FEL) until now.

In section 3, virtual environment technology is defined. A description is given of the structure of virtual environment systems and the components it consists of. The last part of section 3 gives a classification of virtual environments to provide with means for general statements on applicability of the technology.

Section 4 discusses the applicability of virtual environment technology for trainers and simulators. Applicability of different classes of virtual environment systems is determined for several types of trainers and simulators.

To illustrate the use of virtual environment technology for trainers and simulators, we built a sample virtual environment training system. It is described and evaluated in section 5.

Section 6 gives the conclusions of this paper and describes future work we consider.

2 EARLIER WORK BY TNO-FEL

The TNO Physics and Electronics Laboratory has been active on the subject of trainers and simulators for several years. In addition to activities in the field of geometric modelling for visualisation and computer aided instruction, most of the earlier work concentrated on image generation.

2.1 High Performance Computing philosophy

At the basis of our research lies the assumption that High Performance Computing (HPC) tasks like image generation can only be done by systems that rely on parallel processing. We successfully exploited the philosophy that high performance system architectures should be based on a set of interconnected general purpose microprocessors. By using general purpose processors instead of dedicated hardware, system functionality is determined by software. By using a flexible multiprocessor architecture, the system performance can be set by using the right number of processors. Although the main idea is that system functionality is implemented in software, the system architecture should be open enough to allow application specific hardware to be added for certain frequently used low-level functions.

2.2 Visual systems research

The High Performance Computing philosophy was exploited in the area of image generation for visual simulation. This effort resulted in a system architecture with flexible functionality and performance. The strength of the system lies in powerful hardware to provide for fast communication between an arbitrary number of general purpose processors and communication to graphics devices. Software was developed to turn the system into a visual system capable of generating fully textured and anti-aliased images for real-time visualisation with simulation of weather conditions like fog and dusk. This research has yielded basic technology and expert knowledge of visualisation for trainers and simulators.

3 VIRTUAL ENVIRONMENT TECHNOLOGY

3.1 Definition of a virtual environment

One of the problems of virtual environments is the question of how things are named and how named things are defined. It is quite difficult to get a clear understanding of what people mean by 'virtual reality', 'artificial reality', 'cyberspace', and 'virtual worlds'. Attempts to get things clarified were made by Bricken[1,2], Krueger[3] and Rheingold[4].

Inspired by Bricken[1], we choose to talk about a *virtual environment* which is defined as a *multi-dimensional experience which is totally or partly computer generated and can be accepted by the participant as cognitively valid.*

In this rather broad definition of the virtual environment concept, the key idea is that in some way or another, the user's senses are fooled in such a way that a specific environment is experienced. By making the experience realistic and cognitively valid, the user becomes a participant of the simulation rather than a distant user. All this is done by generating a multi-dimensional experience, i.e. stimulate as many human senses as possible. The stimuli should result in a perception that corresponds to the perception that the participant would have in the real counterpart of the virtual environment.

Considering the definition of virtual environment they are not new at all. The classical flight simulator is also a virtual environment. In high-end flight simulators, the human eye, ear and body (via the motion base) receive computer generated stimuli that create the experience of flying a plane. Thus, it is exactly what is specified by the definition.

Virtual environments as they are considered in the media-hype around 'virtual reality' should therefore be considered as an extension of the current virtual environments. The extension was made possible because a number of new human interface devices became available at affordable prices. The various technologies used in virtual environment systems have existed for years, but it is not until now that people put them together in a new way, aiming at a multi-dimensional computer generated experience that makes the user feel as a participant of the virtual environment.

3.2 Structure of a virtual environment system

A virtual environment as defined in the previous section isn't necessarily totally computer generated. On the contrary, in most of the virtual environments, stimuli from the real environment or mock-ups complement the experience of the participant. In general, a virtual environment consists of three different parts, each making up part of the experience of the participant: a computer generated environment, a physically modelled environment and a real environment (see figure 1). These three parts of a virtual environment are described below.

3.2.1 Computer generated environment

Current technology offers a number of means create a computer generated multi-dimensional experience that is needed in virtual environments. In general, the system that creates the computer generated experience consists of three subsystems: a sensor subsystem, a control subsystem and a actuator subsystem. Figure 2 shows these subsystems as part of the entire virtual environment system.

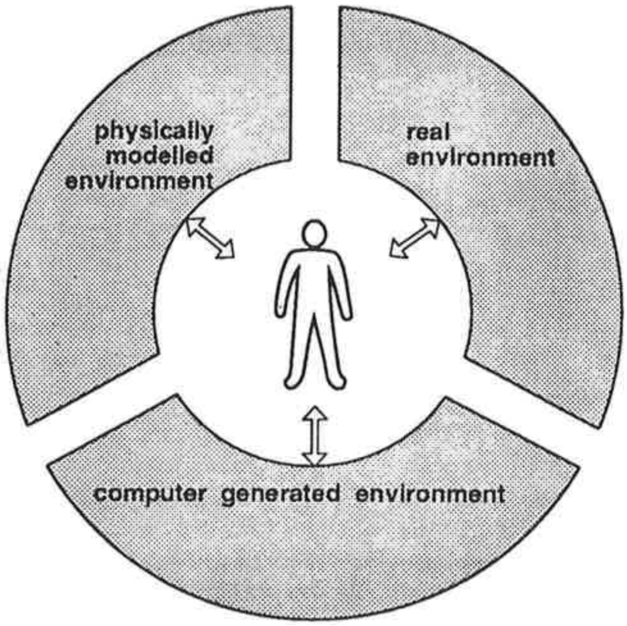

Figure 1. *The three parts of a virtual environment.*

In order to make the experience of the virtual environment cognitively valid, the computer generated experience must adapt to the situation of the participant, the physically modelled environment and the real environment. For example, if the participant moves his or her head, the visual sight that is produced by the system must change. Therefore, we need to now where the head is positioned. As another example, consider a simulator which uses a scale-model of a terrain for the visual sight simulation. In this system, a camera is used to sense the physically modelled environment (the scale-model). This kind of sensing is done by the sensor subsystem.

The control subsystem is a computer that computes what the participant should experience. This subsystem maintains a model of the virtual environment. The model is updated by simulation processes and by the information that comes from the sensor subsystem. The control subsystem outputs signals that describe the experience of the participant.

The actuator subsystem actually generates the computer generated environment. Based on the output of the control subsystem, a number of actuators are used to stimulate the senses of the participant.

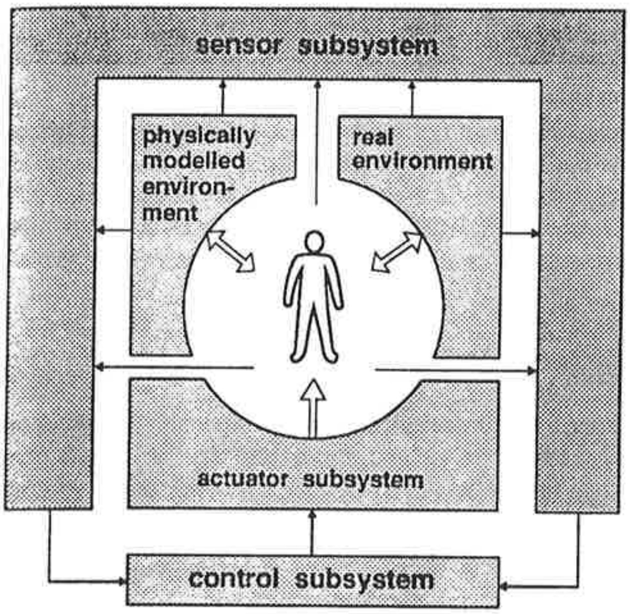

Figure 2. *Structure of a virtual environment system.*

Sensor subsystem

Information on the real world must be acquired to complement the virtual environment model with information that is needed to generate a cognitively valid experience. Several sensors can be used to this end. Most frequently used sensors are:

- general position sensors[4,5]
- hand position sensors[6,7]
- eye gaze direction sensors[8]
- audio sensors including speech recognition

Control subsystem

The control subsystem is the heart of the virtual environment system. The main task of this subsystem is to maintain a model of the virtual environment. For each object in the virtual environment, this model contains a description of the object and state information. The description can contain a geometrical model of the object, visual characteristics, physical characteristics, audio characteristics and many other attributes. The state information can contain position, orientation, acceleration, speed, contact with other objects, etc.

An enormous amount of computational power is required to update the model of the virtual environment. Updates are issued by input from the sensor subsystem and by simulation processes. The latter can be very complex and computationally expensive tasks. Examples of these tasks are the physically correct simulation of object behaviour (statics, dynamics, interaction, deformation, etc.) and collision detection.

Actuator subsystem

The actuator subsystem handles the output side of the virtual environment system and generates the actual experience for the participant. It consists of a set of actuators, each stimulating one of the human senses. It is in this area that a lot of new developments take place. Actuator devices are rapidly improved and costs are getting down. Below, most of the existing actuators are listed:

- head mounted displays[8]
- simple audio reproduction devices
- 3D audio devices[9]
- tactile actuators integrated in gloves[10, 11]
- force actuator[12]

3.2.2 Physically modelled environment

The physically modelled environment consists of physical objects that are more or less a duplicate of objects in the real environment being simulated. These objects also create part of the multi-dimensional experience of the virtual environment. For example, part of a car can be duplicated to create a virtual environment for driving simulation.

3.2.3 Real environment

A virtual environment is not necessarily totally artificial in all aspects. The real environment in which a virtual environment system is placed can be used effectively in creating a realistic and cognitively correct experience. The real environment often generates stimuli for all human senses that can be used in the virtual environment. For example the floor of the real environment can be used to stimulate the tactile senses when simulating walking of the participant. This seems a bit trivial, but it is important to recognise the real environment as a source of stimuli that make up the final experience of the participant.

3.3 Classification of virtual environments

Virtual environments as defined in section 3.1 include a wide variety of systems. A classifications of these systems is needed in order to allow general statements on the applicability for trainers and simulators to be made.

We propose a classification scheme of virtual environments based on a rough quantification of the role of the three different parts of a virtual environment: the computer generated environment, the physically modelled environment and the real environment (see figure 1).

A virtual environment is classified by considering all stimuli that create the multi-dimensional experience, and for each of the three parts of the virtual environment determining what percentage of the stimuli is created by that part. For example, a virtual environment could be build in which 60% of the stimuli is computer generated, 10% origins from the physically modelled environment and 30% from the real environment. Figure 3 shows the classification scheme. Note that only two percentages are needed to describe a specific environment, since the third can be computed from this (the sum of the three must be 100%).

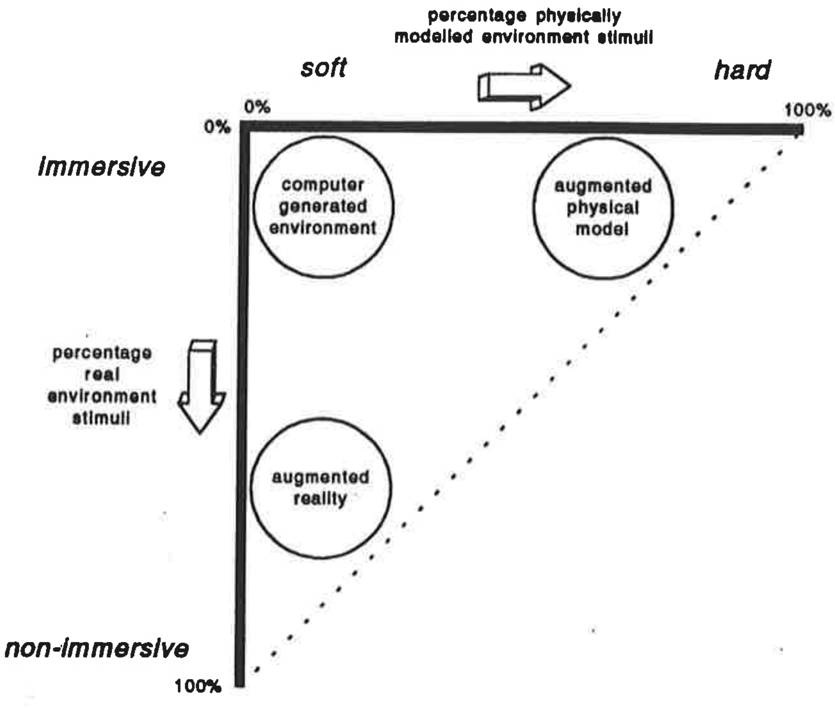

Figure 3. *Classification scheme for virtual environments.*

The classification scheme shows that virtual environments are somewhere between fully immersive or fully non-immersive. In immersive virtual environments, the participant is cut off from the real environment. Visually, this is done by wearing an opaque HMD. Considering audio, it is done by wearing a sound-isolated headphone, or using a sound-isolated room. Note that it is practically impossible to cut off all stimuli from the real environment: it is difficult to switch off gravity, or to disable the haptic stimuli generated by standing on a floor or sitting on a chair.

A second main classification of virtual environments is a division into soft and hard environments. In the extreme case of soft virtual environments, no physical models are used to generate stimuli; whereas in strictly hard virtual environment no computer generated stimuli are used. Correctly speaking, the latter is not a virtual environment as we defined it in section 3.1, since at least part of the virtual environment must be computer generated.

From this scheme, three extreme classes of virtual environments follow. The first class, a computer generated environment, is the ultimate form of a virtual environment: fully soft and immersive. The participant is totally cut of from the real environment, and no physical mock-up objects are used; everything is computer generated.

The second class, augmented physical models, contains hard, immersive environments. In this class, most of the environment is made up by physical models of objects that are used in the environment being simulated.

Virtual environments of the third class, augmented realities, are mainly non-immersive, using a significant amount of stimuli from the real environment, complemented with soft and hard elements. In this class, the real environment is effectively augmented with synthetic elements to create the experience of a virtual environment.

The three classes described above are extreme examples. Practically, a virtual environment will be somewhere in between the three extremes. However, thinking in terms of immersive versus non-immersive environments and soft versus hard virtual environments provides good means for generic conception of virtual environments.

4 VIRTUAL ENVIRONMENTS FOR TRAINING AND SIMULATION

One of the first organisations that has made a significant contribution to virtual environment research is NASA. Since 1984, a number of groundbreaking projects have been conducted at NASA Ames Research Centre. The most important aim of this work was to develop generic, multimodal interfaces, allowing operators to accomplish complex tasks in a natural way[4].

An important aim of trainers and simulators is to help people prepare for the performance of complex tasks. Trainers and simulators are therefore also important potential applications for virtual environment technology. Training is an educational activity that depends to a large extent on participation. The use of virtual environments can dramatically increase the sense of participation in a training situation or simulation, and as a result improve training effectiveness. The applicability of virtual environment technology for training and simulation systems is by no means a matter of course. A useful classification of training systems is the following[13]:

- basic principles (CAI-like systems)
- procedures (partially simulated environment)
- full mission (full replica of environment)

Although this may be too coarse a subdivision, it at least indicates that trainers and simulators vary in complexity from simple, desk-top Computer Aided Instruction (CAI) systems to full replicas of operating environments using full scale mock-ups, functional control desks, motion platforms, etc.

Adding virtual environment technology to basic principles trainers would certainly be feasible at the moment. All classes of virtual environments could be applied here. However, the use of virtual environment technology may be "overkill". Using conventional CAI systems usually is a very cost-effective way of gaining a certain minimum level of educational experience. Adding very expensive virtual environment technology to such a system would probably be an excellent example of the law of diminishing returns. With the advent of much cheaper virtual environment technology, the balance may change however.

The amount of detail required in full mission simulators at the moment poses large problems for the use of virtual environment technology. Specifically, fully immersive, soft virtual environments are hard to use for this kind of trainers. For instance, the generation of high resolution tactile feedback is necessary for the realistic simulation of control panels. Another, more fundamental problem is the simulation of motion cues which at the moment requires very complex and expensive machinery. And what to think of the simulation of micro gravity environments for space applications? For these reasons, we believe that environments for full mission simulators will probably never be completely computer generated.

More opportunities for full mission simulators exist for mixed virtual environments, which use 'non-immersive' and 'hard' elements. Real environment and physically modelled environments can often effectively be used to avoid the problems mentioned above. In this context, see-through HMD's will be very useful. For space-related simulations another problem arises when real environment elements need to be incorporated in the virtual environment. This is often impossible, since training isn't done in space.

It is our opinion that virtual environment technology will be especially useful in the "grey" area in-between the two extremes. In the near future, simple tactile feedback devices will be helpful in eliminating the requirement for physical models of simple control desks, such as those used in part task trainers. Also, the use of see-through display devices will help in getting rid of detailed physical models replacing them with "blanks" that are overlaid with computer generated imagery. Thus, there will be a tendency to more immersive and soft virtual environments. Of course, a certain amount of research into a number of problems with this approach is still necessary.

In the next section, an example will be presented of a procedures trainer, that we hope will illustrate the potential for the use of virtual environment technology for this kind of system.

5 A SAMPLE VIRTUAL ENVIRONMENT FOR EVA PROCEDURES TRAINING

Currently, EVA training programmes that involve the simulation of micro gravity conditions, rely on neutral buoyancy experiments in large water basins[14], or on parabolic flight sorties. Both methods are very expensive because of the high cost of the required equipment, such as swimming pools, aircraft, mock-ups, etc. For the training of EVA procedures, the simulation of a micro gravity environment may not always be necessary, provided the other essential elements of the simulation are convincing enough. In this section we will describe an alternative approach, based on VE technology. Although the VE-based procedures trainer is by no means a fully functional replacement for the other methods of EVA training, it does illustrate a number of points where VE technology may provide a viable solution.

5.1 The Virtual Environment Operating System

The prototype EVA trainer was developed as a demonstrator for a number of techniques used in building VE applications. The system was developed as an application on top of Division Ltd's dVS virtual environment operating system, a basic VE software development and operating platform, running on a number of hardware systems[15].

dVS provides a parallel process model and an object oriented application programmers interface. In order to reduce the complexity of VE simulations, they are decomposed into a number of high-level Objects, which typically correspond directly with physically autonomous objects within the simulated environment. In addition to a representation of their geometry, each of these Objects possesses a number of attributes, such as position, visual, audio, tactile, force, collision, etc. which represent different Elements of the Object.

Elements are handled by autonomous process-like components called Actors. Typically, each Actor takes responsibility for a different Element of the overall environment, e.g. a Visual Actor displays objects on a head-mounted display, using the information of the Visual Elements. The Actors may run in true parallel on different processors, or several Actors may run concurrently on the same processor. The Actors collaborate in the overall simulation by communicating with each other through the services provided by the underlying Virtual Environment Operating System.

A number of standard Actors comes with the dVS package. Most important of these are: the VIZ Actor, which provides stereo views of the Virtual Environment, utilising a head-tracking device to modify the current viewing frustum, the DIRECTOR Actor, which mediates the temporal coherence of all Actors and provides real-time collision detection, and the GLS actor which enables device independent sensor reading.

Thus, standard Actors handle dedicated sensing, control and display tasks, while running in parallel with each other and the application specific Actors. This approach provides the flexibility to expand the system or increase the complexity of the simulation without compromising performance.

5.2 The EVA Trainer application

The EVA trainer was designed to simulate an astronaut, moving around the Columbus Free Flyer (CFF) laboratory and the Hermes spaceplane, using a small hand-held thruster as a means of propulsion. The main parts of the application are the following:

- models of the Columbus Free Flyer and Hermes
- model of the hand-held thruster
- background starfield
- application specific software (the EVA Actor)

The models of the CFF laboratory and the Hermes spaceplane were made with our in-house modelling software. A simple filter program was written to convert the data from the hierarchical PHIGS file format, used in this software to the PAZ format, required by the dVS rendering software.

The hand-held thrusters were not modelled to accurately represent a real-world device, but merely to act as an iconic representation, helping the participant to approximate thrust vectors, relying on visual feedback. The thruster icon follows the movement of the 3D mouse (a simple joystick-like device with a position sensor attached to it) device being held by the participant. The 3D mouse contains 2 buttons under the participant's thumb, used to activate thrust and retro-thrust respectively, and a trigger, operated by the participant's index finger, used to pick-up objects that are touched with the thruster icon. In order to give the participant some feedback on the operation of the thruster, a simulated exhaust plume is displayed and a hissing sound is produced in the HMD's headphones when the thruster is operated.

The background starfield consists of several hundreds of the closest stars, i.e., within a distance of about 50 light-years from the sun. Their positions were obtained from a publicly accessible database.

For the application specific part of the software, new Actor software was developed to implement the EVA-specific functions. This software is responsible for the simulation of the astronaut's motion and the opening and closing of the CFF storage bay hatches. Additionally, some functionality was included for a simple console interface, which allows the selection of motion models, calibration of the participant's centre of mass, and resetting object positions.

The model that governs the participant's motion in virtual space is based on the equations of motion for a simple rigid body[16]. The motion of a rigid body can always be considered as a combination of a translation of its centre of mass, and a rotation about an axis through the centre of mass. Computation of the change in motion of the astronaut who executes a course correction by applying thrust in some direction proceeds as follows:

- The state of the 3D mouse buttons used to activate thrust and reverse thrust is sampled every 1/30th of a second. If neither of them is depressed, both the translational velocity and the rotational momentum remain constant
- If either thrust or retro-thrust are applied, the change in translational velocity is simply calculated using Newton's second law. The torque that results from the thrust being applied at the end of the astronaut's extended arm leads to a change of rotational momentum. By taking into account the moments of inertia of the astronaut's body, the change in the rotational velocity vector can be computed.

By using the handhold thruster, the participant is able to move through virtual space, open and close the storage bay hatches of the CFF by touching them with the thruster icon and retrieve box-like objects from the storage bay by picking them up with the 3D mouse. This scenario provides the basis for the simulation of ORU exchange procedures.

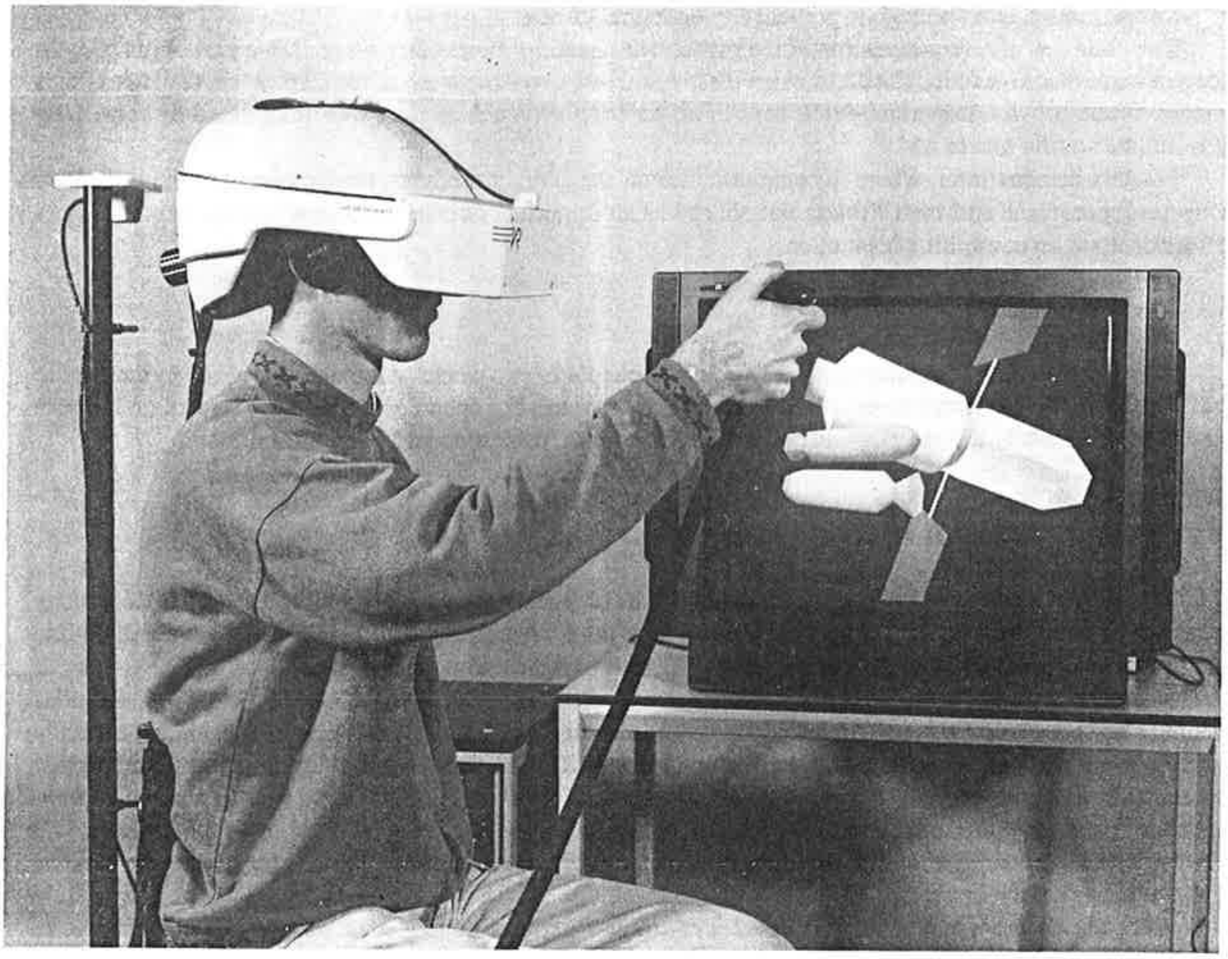

Figure 4. *The VE-based EVA procedures training system*

5.3 Evaluation

As has been stated before, the VE-based EVA Trainer by no means is a ready replacement for the existing training facilities, nor was it meant to be. In addition to this, no formal evaluation of the usability of the VE-based system has been undertaken to date. However, several points can already be addressed.

5.3.1 Simulation fidelity

The crucial element for a procedures trainer such as this is the fidelity with which the movement through space and the various steps of an ORU exchange are experienced by the trainee. The ORU exchange scenario is not simulated very accurately, but the fact that the correct equations of motion were used, proved very convincing to people with experience of real or simulated EVA procedures. This indicates that with more accurate models of actual ORU's, the CFF storage area, and perhaps some simple form of tactile feedback, an effective procedures trainer can be realised.

5.3.2 Visuals

The resolution of the head-mounted display is currently one of the factors that limits the usability of the VE-based system. The rendering hardware of our system is capable of generating images at resolutions of up to 748 by 480 pixels (for each eye). However, the LCD technology used in the display allows an effective spatial resolution of 320 by 240 pixels per eye. In practice this means that, for instance, the stars in the background have to be placed in virtual space at a distance that is so small that some motion parallax is sometimes evident when moving further away from the centre of virtual space. For comparison we attached a standard NTSC TV receiver to one of the display controllers. On this screen, the stars were easily visible at distances of at least 3 times as great, which is far enough to prevent any unnatural effects.

The omission of a representation of the participant's hand, or some other recognisable part of his body or space suit sometimes made it difficult to judge distances when operating close to the CFF. Also, the lack of cast shadows, which provide important depth cues in an environment such as this, was often noted as something that would be worthwhile to add.

For this demonstrator, where the emphasis lies on the EVA procedures, the simplicity of the models of the Hermes spaceplane and the CFF was not noticed as an important deficiency, because the participant has to fully concentrate on controlling his motion.

5.3.3 Development effort

The VE-based demonstrator was developed by 2 people in two weeks. Although we would be the first to admit that a lot of work needs to be done to extend it to a system for operational use, these figures do indicate the potential benefits of the use of a standard software platform, using standard development tools.

6. CONCLUSION AND FUTURE WORK

In this final section we will draw conclusions, both regarding the general applicability of VE technology for trainers and simulators, and from our experience with the EVA training demonstrator. Also, we will outline some of the work that will be undertaken at TNO-FEL in the near future.

In general we have become convinced that VE technology offers many opportunities for new generations of training and simulation systems. In particular, immersive and soft virtual environments will almost certainly provide a good basis for more effective procedures trainers. On the other hand, fully immersive, soft virtual environments will probably never be applicable in the case of full-mission trainers. A certain amount of non-immersive, physically mediated environment will always be required here. For basic principle trainers, VE technology would be applicable if it were cheap enough, but in the immediate future it looks like the benefits would not outweigh the costs.

After the development of the VE-based EVA trainer our preliminary conclusion is that the concept of using an immersive, (almost) soft virtual environment for a procedures trainer has been proven. Furthermore, the use of commercial off-the-shelf components has radically shortened the development time for the prototype.

In the near future, research and development efforts at TNO-FEL will proceed from those related to strictly visual simulations to "rich" virtual environment simulations. Some of the issues that we intend to pursue actively, are:

- achieve better and more realistic images using texture and shadowing
- employ more complex physically correct simulation models for, e.g., collision detection, dynamic behaviour of objects, etc.
- apply our own HPC platform[17] to virtual environment simulation
- develop new software development techniques and tools for HPC computing
- investigate possibilities for tactile and force feedback
- research into new modelling primitives for real-time visual simulation
- properly evaluate training effectiveness of VE-based trainers

The applications primarily considered are training and simulation systems, but results will be useful for other purposes as well, such as interactive modelling and tele-operation.

Contrary to what the press sometimes wants us to believe, virtual environment technology is nothing magical, but rather a synergy of various technologies that by themselves are already known. Expertise on each of these technologies has been in existence within the TNO organisation for a more or less longer period of time. We therefore expect to be able to make significant progress in applying VE technology in a number of defence and aerospace related areas.

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