Available online at www.sciencedirect.com
SCIENCE DIRECT
Int. J. Human-Computer Studies 64 (2006) 182–191
International Journal of Human-Computer Studies
www.elsevier.com/locate/ijhcs

Multimodal astronaut virtual training prototype

Jukka Rönkkö[a], Jussi Markkanen[a,*], Raimo Launonen[a], Marinella Ferrino[b], Enrico Gaia[b], Valter Basso[b], Harshada Patel[c], Mirabelle D'Cruz[c], Seppo Laukkanen[d]

[a]VTT Technical Research Centre of Finland, 02100 Espoo, Finland
[b]Alenia Spazio S.p.A, Strada Antica di Collegno, 253 10146 Torino, Italy
[c]VIRART, University of Nottingham, University Park, Nottingham, NG7 2RD, UK
[d]SenseTrix, PL 23, 02771 Espoo, Finland

Available online 29 September 2005

Abstract

A few dedicated training simulator applications exist that mix realistic interaction devices—like real cockpits in flight simulators—with virtual environment (VE) components. Dedicated virtual reality (VR) systems have been utilized also in astronaut training. However there are no detailed descriptions of projection wall VR systems and related interaction techniques for astronaut assembly training in zero gravity conditions. Back projection technology tends to have certain advantages over head mounted displays including less simulation sickness and less restricted user movement. A prototype was built to evaluate the usefulness of projection technology VEs and interaction techniques for astronaut training. This was achieved by first constructing a PC cluster-based general purpose VE software and hardware platform. This platform was used to implement a testing prototype for astronaut assembly sequence training. An interaction tool battery was designed for the purposes of viewpoint control and object handling. A selected training task was implemented as a case study for further analysis based on laptop usage in the Fluid Science Laboratory (FSL) inside the Columbus module in the International Space Station (ISS). User tests were conducted on the usability of the prototype for the intended training purpose. The results seem to indicate that projection technology-based VE systems and suitably selected interaction techniques can be successfully utilized in zero gravity training operations.

1. Introduction

In the VIEW of the Future EU project (VIEW, 2003; Wilson et al., this issue), research and development consisted of two application streams, for the automotive and space industries. In the latter the work focused on using virtual reality (VR) in space operations related activities, specifically astronaut training for assembly tasks performed in a zero gravity environment. It was thought that VR could be used as an efficient tool for tasks that are difficult and expensive to reproduce otherwise. An assembly sequence training task in orbit conditions on the International Space Station (ISS) was selected to investigate the usefulness of a virtual tool.

Astronaut working environments in orbit consist of zero gravity conditions, which affect the way objects can be manipulated and how the astronauts move. In addition to this, indoor operations are performed in confined quarters. Astronaut training methods have traditionally included classroom training, multimedia presentations, physical mock-up and swimming pool-based training as well as parabolic flights. An overview of the current astronaut training program is available at ESA (2004). Existing training methods rarely cover the aspects related to object handling in zero gravity. The methods that do address these aspects, such as parabolic flights, are very expensive and are not easily accessible. Another factor is related to the availability of physical prototypes. The tendency in the modern industrial world is to move towards shorter product life cycles. This is also the case in the space

*Corresponding author. Fax: +358 9 4567049.
E-mail addresses: jukka.ronkko@vtt.fi (J. Rönkkö), jussi.markkanen@vtt.fi (J. Markkanen), mferrino@to.alespazio.it (M. Ferrino), harshada.patel@nottingham.ac.uk (H. Patel), seppo.laukkanen@sensetrix.com (S. Laukkanen).

1071-5819/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijhcs.2005.08.004

industry, therefore starting the training procedures with virtual products in preference to physical prototypes would offer clear benefits in terms of time spent from design to utilization.

One of the central pieces of work in the VIEW project was the User Requirements Document (URD), which listed and prioritized the user needs. The URD described the needs of zero gravity-based assembly training tasks performed at the International Space Station. Bearing in mind the state of the art of VR technology and the URD, a low cost VR hardware system set-up was designed, implemented and installed at both Alenia Spazio (the user company) and VTT Information Technology (the developer) premises. Concurrently, a software platform was developed that could address the needs of the hands-on assembly training in the zero gravity environment. This was due to the fact that at that stage of the project there were no off-the-shelf solutions available, which would offer features like a reasonable content creation pipeline for VR simulation and scenario editing, collision detection and dynamics for zero gravity, low cost and re-configurablity of hardware. The developed platform was utilized in the development of a prototype that implemented a selected assembly training task normally performed at ISS.

Following a description of the platform, this paper describes the interaction technique battery that was designed (Rönkkö et al., 2003), thought to sufficiently mimic real world user interaction according to the stated user needs as well as to avoid the problems related to the current technology. Then the preliminary set of user tests conducted at the Alenia installation are described. The tests indicate the necessary further development steps from the usability standpoint for zero gravity training, but also indicate that VR simulations can be beneficial in this field. They also indicate that projection wall-based systems equipped with VR interaction devices, such as datagloves, can be successfully utilized in this type of training. This means that physical mock-ups are not necessary for all training purposes.

In practice the approach was an iterative workflow, in which the user requirements affected the technical choices made. On the other hand issues related to the present day technology affected the prioritization of the features in the implementation, for example, the cost of producing relatively accurate force feedback to the user's hands and fingers was considered prohibitive.

2. Related work

The work presented in this paper connects to research in the fields of anthropology, ergonomics, and the social factors of the way people live and operate in extreme environments like space (Meinster, 1986; Connors, 2001; Manzey, 2003, Masali and Ferrino, 2004). An example of a multi-disciplinary approach has been developed during the HABITATION module design definition activities, including proxemics and anthropological methods (Ferrino and Gaia, 2003; Ferrino, 2004). This work started from observation of performance in orbit, focused on orientation, visual interaction, proximity and dimensional and environmental constraints.

In relation to the specific task context for our project, behaviour, posture and interface analysis in a zero gravity environment related to laptop usage have been studied (Burzio et al., 2003). Astronauts find quite different ways to use the laptop in zero gravity compared to on earth, and even the whole design of the normal laptop concept is found to be questionable for the zero gravity environment. This suggests that training which gives first hand experience of object movement in zero gravity may be beneficial compared to training that relies partly on the imagination of the trainees, such as classroom training on earth.

The way to discover how training can be implemented effectively in VR is not trivial. Computer based training (CBT) problems, like those related to the lack of personal interaction as found in instructor-led training (ILT), can be present also in VR training systems. For example, the lack of an instructor may limit the number of ways a certain task can be correctly performed in virtual environments (VEs) compared to reality. The effectiveness of CBT can also be affected by the computer skills and the attitudes of the trainee. This is a particularly important issue regarding VR technologies, where a number of new devices can be introduced to the trainee. Some studies have shown that training using VEs has been hindered by the technology and it is sometimes difficult to know whether any improvements in performance show that the trainee has learnt the specifics of the task or just how to use the technology effectively (D'Cruz, 1999).

VE techniques have been used in astronaut and ground-based personnel training to prepare for the Hubble Space Telescope repair (Loftin and Kenney, 1995). The conclusions were that the use of the VE simulation had a positive impact on acquiring the knowledge for the mission. However, a detailed description of the interaction was not presented. Montgomery et al. (2001) have studied VE training for biological microgravity experiments with and without haptic feedback.

Computer graphics-based interaction can be thought to be a composition of basic interaction tasks (Foley et al., 1996). This classification has been commonly used in the context of VR user interaction and is refined by others (Bowman, 1999). These tasks include object indication, selection, orienting, moving, creation and deletion, text input as well as viewpoint and system control. The basic tasks can be implemented in a multimodal fashion, which means that multiple communication channels are used between the user and a computer, such as speech, hand and head tracking as well as gestures. The use of these input channels should be complementary rather than redundant (Bowman and Hodges, 1997). Billinghurst (1998) and Oviatt (1999) point out other principles to be taken into account in designing multimodal input. For example, speech should be used for non-graphical command and control, gestures for visual/spatial input. VEs have been used in assembly simulation with multimodal input

(Zachmann, 2000) with outcomes supporting Billinghurst's guidelines.

3. User requirements and the test task selection

One of the central aims of the overall research programme was to enhance the future workplace through the use of VE-based tools. To achieve this the VIEW industrial partners (Alenia Spazio, John Deere, PSA Peugeot Citroën, Volvo) contributed workplace descriptions and scenarios of work processes for a set of existing tasks to the URD. These were used to extract requirements that were collated and prioritized. In the VIEW space stream Alenia Spazio provided scenarios for a set of assembly tasks that astronauts perform on the ISS and scenarios for on-ground equipment testing. From the space stream point of view, the VE-based tools could be useful in training, design and planning and simulation. Training for the assembly sequence in orbit on the ISS was selected to be the main field of interest. These assembly tasks on the ISS require actions such as handling freely floating objects, connecting and disconnecting parts, pushing buttons, turning switches on and off and opening and closing lids. While performing these operations, the astronaut may have to move by grabbing handles placed along the walls and ceilings of the corridors of the ISS modules and hook his or her feet on special loops to avoid floating away. The main focus of training for this type of task is the correct sequence of these operations as well as becoming familiar with the general object behaviour and movement in zero gravity. Fine-grained manipulation tasks requiring fine motor control—like using a screwdriver—are not the center of interest within this context, because such elementary tasks are assumed to be very well known to the trainees.

A specific task was selected to test the ideas related to VE-based training. This task was laptop installation to a wall mounted Fluid Science Laboratory (FSL) rack inside the Columbus module in the ISS. The rationale behind the selection of this task was that the real FSL hardware was available at Alenia to be able to make comparisons of operations in normal gravity and the operations in the VR mock up. The real movements analyses of the FSL tasks were developed in the context of the EU Project REAL MAN IST-2000-29357. The laptop installation scenario was also seen as a good case study and a good starting point to orient human posture analysis, and to create innovative design concepts in future projects.

4. Platform description

One of the main technical choices in VR platform design is to select either a projector screen (Cruz-Neira et al., 1993) or a head mounted display-based solution (HMD) (Kalawsky, 1993). HMD solutions have several good aspects like no occlusion problems between the viewable imagery and the users' limbs. Negative factors include the fact that users may be more susceptible to simulation sickness. Projector-based solutions—especially if reconfigurable—can be used for other presentation purposes and not only for VR. This resulted in the selection of a projector screen-based solution. When the VIEW project started few solutions existed for relatively mobile, low cost and reconfigurable rear projection system set-ups with suitable interaction options that could be bought off-the-shelf.

In addition to hardware there were URD requirements that indicated possible difficulties with the VR software systems that existed at the time, such as demands for the simulation of variable gravity environments; this required the possibility to integrate real-time dynamics and collision detection to the core of the VR system, otherwise in a distributed system synchronization problems can occur. Another major issue is the content creation pipeline for the system. It was necessary that VR content could be created for the scenarios from existing CAD models. However visual geometries are only one part of the content, that also includes auditory information for collisions and physical object and other entity properties such as mass, collision geometry and joint properties. The authors of the scenarios required tools to design these parameters. There was no readily utilizable combined solution that would provide a reasonable content creation pipeline for the type of data required, physics-based simulation, PC-based low cost distributed and scaleable architecture and re-configurable hardware.

Therefore the design of a system of this type, as well as the development of suitable software to run the system, took place at the beginning of the project. The system—called the VE-View hardware and software platform—was targeted to be low cost, PC based and modular, later expandable and reconfigurable in terms of screen numbers and locations. The hardware set-up of the display system is shown in Fig. 1. The main hardware components of the system are:

- Two movable rear projection screens
- Two movable mirrors

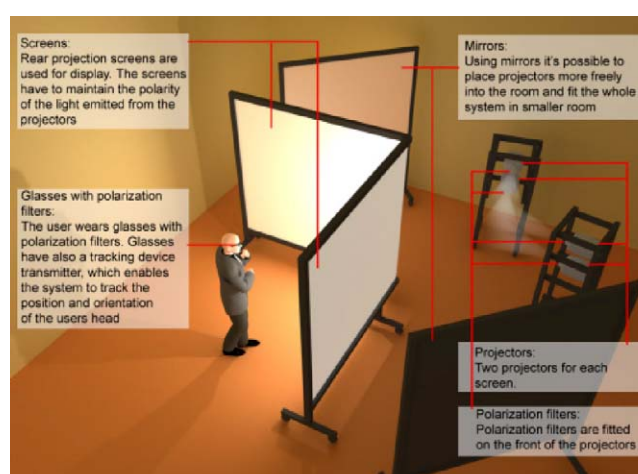

Fig. 1. VE-View hardware, rear-projection display set-up.

- Adjustable projector mounts, two LCD projectors located in each mount
- Four rendering PCs (2.0 GHz, GeForce4 graphics cards, 512 MB memory), two per wall, one for each eye
- Control PC (similar to rendering PC, 1 GB memory)
- Laptop for dataglove connections and speech recognition
- Audio server PC
- 5th Dimension datagloves
- Connexion3D Spacemouse
- IS600 Intersense tracker or A.R.T optical tracker for head and hand tracking
- Gigabit switch for networking all the computers together

The VE-View hardware platform includes custom made components for mounting the projectors and for movable mirrors and screen frames. The structure of the system allows reconfiguration of the system, for example, from the L-shape to a single big powerwall or to utilize one screen alone. Fig. 2 shows the system in use in the L-shaped configuration. This concept is inspired by systems like FLEX from Fakespace (2004), however even though the system can include multiple screens, emphasis has been also on the ease of transportation of the whole system in and out of the original installation site. This is due to the fact that the projector mounts and screen frames are collapsible and equipped with wheels.

The VE-View software platform is used to control the hardware and to implement the zero gravity assembly training prototype, including a selected set of interaction techniques. It is a distributed client server system developed by VTT Information Technology. One of its technical core aims is to research the suitability of game technology for VR applications (Rönkkö, 2004). It utilizes rigid body dynamics to produce realistic object behaviour like collisions and kinematics needed in zero gravity simulations. It also provides facilities for multimodal input via datagloves, trackers and speech. The platform includes tools that allow the design of the scenario surroundings and related physical constraints with a commonly used 3D modelling package without programming expertise. However scenario specific actions require the use of the programming API provided by the system.

Fig. 2. The L-shaped system in use.

5. Interaction techniques for the astronaut training prototype

The VE-View software platform was used to develop an astronaut training prototype and the laptop installation task into the FSL rack on the ISS. The interaction involved is in three main categories: object manipulation, viewpoint control and system control. In the implemented training task there are two users: the trainee and the trainer. As the role of the trainer is mostly to give instructions, his or her interaction with the system is mostly limited to viewpoint control. The more comprehensive set of interaction techniques is in use by the trainee.

The interaction techniques have been designed or selected bearing in mind resemblance to real world behaviour in assembly training tasks. For example, we selected datagloves as interaction devices for object manipulation as the astronauts use their hands to manipulate objects. However, really fine-grained manipulation, such as using one's fingertips to rotate small objects, is not possible. This is due to the limitations of the accuracy of the dataglove input as well as the lack of haptic feedback (beyond the resources for this development). On the other hand fine-grained manipulation was not the main target of the training task. The idea was to study the generally realistic object behaviour in zero gravity and the correct assembly sequence.

To mimic real world behaviour two-handed interaction can be used. The behaviour of the objects is determined by rigid body dynamics including inertia properties and collision detection. The gravity conditions affect the object behaviour and the level of gravity can be adjusted, as was required by the URD. The represented techniques comprise an interaction technique battery that was presented in its early form in Rönkkö et al. (2003) and now in a refined form as a result of initial user feedback. This initial, informal feedback was received from a small group of users of variable ages that visited our facility in conjunction with demonstrations of the prototype. They had little or no prior VR experience.

5.1. Object manipulation

At this point only the trainee is capable of directly interacting with the physically simulated environment. Object manipulation is performed with virtual hand manipulators. The manipulators consist of a collision body representing the hand itself and a sensor object that is offset from the collision body of each hand. The positions of the collision bodies of each hand are determined as a combination of the transformation data from the trackers, navigational position and orientation of the user as well as rigid body physics calculations. Although in the initial presentation of the interaction technique battery the

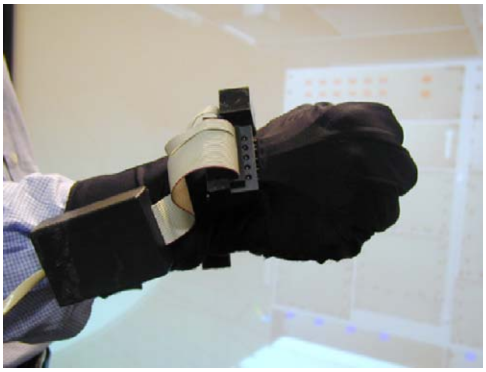

Fig. 3. The grabbing gesture.

manipulators included a visual presentation of the user's hand in the virtual world, in the later version only the sensor objects are visible. This is due to the confusion expressed by users concerning the four different moving objects, two virtual hands and two sensor objects. As the hand manipulators are represented in the simulated physical world by a body with collision and dynamics properties, a realistic virtual hand movement is obtained when they collide with other objects, as well as clamping of the virtual hand movements if they collide with static objects.

Some inaccuracy in the dataglove finger flexure measurements have led us to discard at this point the real world way of touching, grabbing and moving of objects. Rather an object can be indicated by touching it with the sensor object associated with each hand. An indicated object can be selected and grabbed by clenching fingers into a fist gesture (see Fig. 3). After this, the object is attached to the virtual hand and can be moved and rotated. The object can be released by changing the gesture from the fist gesture to something else. When the user does not want to explicitly grab an object, the virtual hand manipulator can still interact with other objects through its collision and dynamics body. Therefore it is possible to push objects with one's hands.

The user is provided with additional feedback of his or her interaction by visual and audio cues. The audio feedback results from the collisions of or with objects or if a certain phase in the manipulation sequence has been successfully completed, such as opening a lid. Indicating an object causes it to be highlighted. The highlight mechanism is implemented by creating a temporary, semi-transparent and brightly coloured replica of the original object, which is slightly larger than the original object and located at the same position.

5.2. Viewpoint control

The position of the trainee in the VE is a combination of the tracked head position and their navigational position. Both users, the trainer and the trainee, can control the navigational position of the trainee in the virtual world. In this manner the trainee is free to move around, but in case he or she is uncertain of the suitable location for the next operation to be completed the trainer can help the trainee to move to a certain location. As an intermediate solution the trainee moves by gestures such as shown in Fig. 4. In reality the astronauts move by grabbing and pulling from handles attached to the structures of the ISS. The trainer can control the navigational position by a space mouse, which is a 3D interaction device used in CAD design.

5.3. System control

System commands and controlling the simulation in general are handled via a gesture directed menu or speech commands, for example, commands that affect the gravity levels. System control is a task that should interfere little with the training itself. Using speech in system control allows other tasks (viewpoint control and handling of objects) to be carried out with little or no interruption. However, if there are a lot of commands that should be memorized, speech input increases the learning curve. Therefore the visual representation—a menu—of the available options is required. The menu can be activated by holding a hand in the fist gesture for a few seconds, provided that the hand is not colliding with anything. The menu selections can be made by moving the tracked hand up and down the menu structure. In the initial user tests only the gesture directed menu version was tested.

6. User tests

User tests were carried out at the Alenia Spazio site. The main targets of the tests were to clarify the usability of the devices and the interaction techniques as well as to evaluate the overall usefulness of the set-up in non-fine grained assembly tasks in zero gravity. The real FSL rack used in the laptop installation task is also available at the Alenia site, however formal comparison studies between the real and the virtual case were not performed at this stage. Fig. 5 shows pictures from the tasks being performed both with the real and the virtual mock-up.

In the assembly task the FSL workbench is integrated in the FSL rack as a passive drawer, containing the laptop computer on a sliding tray. The workbench set-up includes sliding out and fixing the drawer, of which upper side is used as a working platform to support and fix objects for nominal operations or maintenance as required. The Alenia trials were based on the tasks related to the extraction of a laptop computer and fixation of the laptop on the tray. The user can pull the tray out from the drawer after he or she has opened a lid. Fig. 6 shows a user opening a lid in the drawer.

In a normal gravity environment the main requirement that characterizes the laptop usability is the possibility to work irrespective of location and time. The laptop is seen as a typical "gravitational" object that rests on the lap, knees, desk or table for short work periods. In zero gravity none of these requirements are satisfied. The object can be

Fig. 4. Gestures used to move forward, backward and to turn right.

Fig. 5. On Earth set-up and virtual environment simulation.

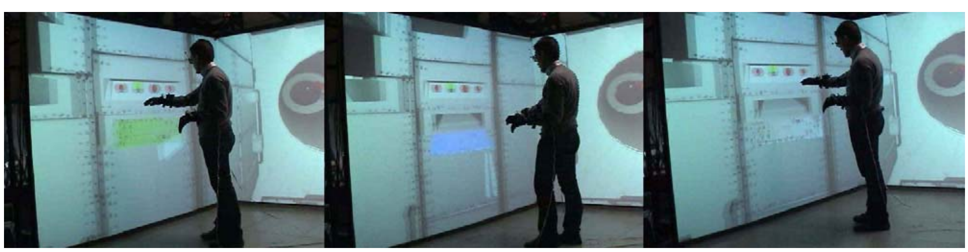

Fig. 6. Selecting, opening and releasing a lid of the drawer in the FSL rack.

held in the hands or fixed on various kinds of dedicated restraints (velcro, tethers, handrails, handles) or simply float in space. The consequence of this is that users are free to use standard items in an unconventional manner and to establish their own methods of object manipulation.

The system was prepared for each user before they performed the tests, which included dataglove gesture calibration to suit each individual (shown in Fig. 7). The users had a briefing, in which the task was described and shown to them step by step. They familiarized themselves with the interaction devices before performing the actual task. The users took as long as they needed to perform the task.

Fig. 7. Glove calibration.

6.1. Participants

Twelve participants (nine male and three female) aged between 21 and 46 years (mean: 32 years) completed the experiment. Five of the participants were students, six were engineers and one participant was an astronaut. Four of the participants had some previous limited experience of using VR, and three participants were familiar with the FSL.

6.2. Questionnaires

General usability/menu usability/interaction device questionnaires were developed by VIRART at the University of

Nottingham through structured expert discussion within the project, adaptation of questions from existing questionnaires and applying themes emerging from Barfield et al. (1998) and Kalawsky (1999).

Participants answered each question on a five point rating scale which ranged from strongly agree to strongly disagree. These ratings were converted to numerical scores with strongly agree given a score of 5 and strongly disagree given a score of 1 (converting negatively worded questions). The maximum possible total score for each question, taking into account all participant data, was 60 (12 participants $\times$ maximum score of 5 for each question). These scores were converted into mean scores to account for any omissions in the data (maximum score of 5.0). Mean scores that are a value of 0.5 or more away from the neutral score of 3.0 are seen as indicative of a trend towards agreeing or disagreeing with a particular statement. The data from the questionnaires are discussed in terms of mean scores and the general trend of participant scores because there are no previous data for statistical comparison (see Table 1).

6.3. General usability questionnaire

6.3.1. Fidelity of the VE/Display system

Participants generally found that the objects in the VE were very realistic (mean 3.58) and were able to recognize all the objects. Generally participants were happy with the way the display system showed the VE (mean 3.5). Participants were very positive about the use of sound in the VE, and many thought that it improved their performance (mean 3.83), and equally importantly, they liked the use of sound (mean 4.0).

6.3.2. Ease of use

Participants found it easy to learn how to use the VR system (mean 3.83), and found the system easy to use (mean 3.58). However, most participants reported that they thought it would be easier to use the system if they had more practice (mean 3.67). Generally, participants found the VR system to be user-friendly (mean 3.5) and all participants enjoyed performing the task in the VR system (mean 4.33). In addition, participants reported feeling a high level of presence in the VE (mean 3.92).

6.3.3. Navigation and object manipulation

Most participants reported that they could effectively manipulate objects in the VE (mean 3.75) and most participants did not easily became lost or disorientated in the VE (mean 4.0). Generally, participants found that when necessary they were unable to make precise movements in the VE (mean 2.33). Some participant comments suggested that this was due to the glove. Most participants agreed that after performing an action it was easy to see that the action had been carried out (mean 3.5).

6.4. Interaction device usability questionnaire

Nearly all participants found it easy to understand how to use the glove to interact with the VE (mean 3.92). However, the majority of participants did not think that the glove gave them good control over their interaction with the VE (mean 2.5). Most participants reported that they did not find the glove complicated to use (mean 3.5). However, the majority of participants found it difficult to move and position themselves in the VE using the glove (mean 2.58), though only three participants found that using the glove decreased their desire to move around within the environment (mean 3.58). Most participants enjoyed using the glove (mean 3.67), however, three participants reported feeling physical discomfort when using the glove to interact with the VE (mean 3.58).

6.5. Participant comments

It is worth noting that the astronaut participant found that the system was easy to learn and was an effective demonstration of the technology, with much potential for procedures training and COL module orientation. He found it easy to move and position himself in the VE using the glove but commented that the gloves were a bit too big. Other participants also found that the gloves were too big or the electronics box on the glove was too heavy, which caused the gloves to twist and made their response to gestures less predictable. Some participants found it difficult to select objects using the glove, and noticed a lag between commands and actions being carried out. Generally, all participants were positive about, and enjoyed, the virtual experience.

7. Discussion

The initial user tests indicate that this particular prototype application was easy to learn, enjoyable, with reports of a high level of feelings of presence. The users found the use of audio feedback valuable. The astronaut participant commented that this technology has a lot of promise. Participants found it difficult to navigate using gestures, however it is worth noting that using gestures is an intermediate step as the real world movement is achieved by grabbing handles. Using the glove was problematic for some users and many felt that it was too big. It was also noticed that the gesture recognition rate is rather poor even after calibration for users with small hands. In addition, the glove itself may introduce discomfort due to the rather large electronics box that is attached to it. However, the method of interacting with the gloves seems intuitive. Therefore better device options and glove fittings should be designed in the future. Before these changes are made it is difficult to comment on the imprecision of object manipulation. The optical A.R.T tracker used in the tests gives millimetre range accuracy so a great part of this feeling could come from the operation

Table 1
Mean scores for each of the statements in the usability questionnaires, where 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree

	Mean	Standard deviation
Usability questionnaire statements		
Objects in the VE were very realistic	3.58	0.67
There were no distortions in the VE images	3.00	0.85
I was happy with the way the display system showed the VE	3.50	0.67
I found it difficult to learn how to use the VR system	3.83	1.27
I found it easy to use the VR system	3.58	1.24
I think it would be easier to use the system if I had more practise	3.67	1.15
I could effectively move around and manipulate objects in the VE	3.75	0.75
I think that I would feel uncomfortable using this system for long periods of time	3.42	0.90
I felt like I was in control in the VE	3.33	0.98
I thought that the visual quality of the VE was good	3.67	0.49
I think that audio (sound) feedback (when used) improved my performance on the task	3.83	0.83
I liked the use of sound in the VE	4.00	0.74
I did not notice any disturbing lag or delay between my movements of the controls and the response in the VE to my actions	2.83	1.34
My general sense of presence (feeling of 'being there') in the VE was high	3.92	0.51
I could move easily through the VE	3.00	1.13
I easily became lost or disorientated in the VE	4.00	0.85
I was able to recognize all the objects in the VE	4.17	0.39
After performing an action it was easy to see that the action had been carried out	3.50	0.90
It was difficult to see which objects I could interact with in the VE	3.33	0.65
I found it difficult to interact with objects in the VE	3.25	0.97
When necessary I was unable to make precise movements in the VE	2.33	0.65
I kept making mistakes whilst using the zero gravity VE	2.83	0.83
I felt that I performed the task well in the VE	3.42	1.00
The VR system is user-friendly	3.50	0.90
I enjoyed performing the task in the VR system	4.33	0.49
I clearly understood how to perform my task but I wasn't able to do this easily in the VE	3.33	0.98
Menu usability questionnaire statements		
I found it easy to select the menu in the VE	2.75	1.29
I found it easy to understand how to use the menu in the VE	3.25	1.14
It was time consuming to access the appropriate menu options	2.92	0.79
It was easy to select the desired menu option once I had located it	2.75	0.87
Obvious cues were provided to indicate that I had selected a particular menu icon/option	2.92	1.08
I found it frustrating to use the menu	3.25	1.14
I enjoyed using the menu	2.75	0.75
Input device usability questionnaire		
I found it easy to understand how to use the glove input device to interact with the VE	3.92	0.79
The glove input device gave me good control over my interaction with the VE	2.50	0.90
Using the glove input device distracted me from the task I was performing in the VE	3.42	0.79
The glove input device was complicated to use	3.50	0.80
I found it easy to move and position myself in the VE using the glove input device	2.58	0.79
It was easy to select and move objects in the VE	3.17	1.19
It was uncomfortable to use the glove input device	3.25	0.75
It felt natural to use the glove input device to control my movement in the VE	3.33	0.98
Using the glove input device decreased my desire to move around within the environment	3.58	1.16
The glove input device made it easy for me to interact with the VE	3.17	0.94
I found it frustrating to use the glove input device	3.42	0.79
Using a different input device would have made it easier to move around the VE	3.42	1.08
I enjoyed using the glove input device	3.67	0.78
I kept making mistakes when using the glove input device	3.17	1.02
I found it easy to correct any mistakes that I made when using the glove input device	2.92	0.90
It was easy to make the required gestures to interact with the VE	3.17	0.83
I did not experience any physical discomfort when using the glove input device to interact with the VE	3.58	1.08
The gloves fit my hands well, i.e. they were a comfortable fit	2.83	1.11
It was easy to perform gestures using the glove input device	3.42	0.79

of the glove or from the lack of haptic feedback. However fine-grained manipulation was not one of the main targets of this prototype. In conjunction with improving the glove interface, the menu structure should also be improved as it did not rate very highly in the user test. In further user tests the speech menu interface should also be tested.

Further extensive testing is required in order to make more detailed comparisons of the benefits of using real and virtual mock-ups. We need to introduce more task sequences and more detailed interfaces as well as more potential users. However, in general it seems that the technology is very promising and that it is possible to build very useful tools for astronaut training in zero gravity environments using low-cost PC hardware and back projection screen technology. Especially when physical mock-ups are not available, VR technologies can be beneficial. The system set-up also turned out to be successful in the sense that we were able to move relevant parts of the system relatively easily to give demonstrations in locations other than Alenia or VTT.

8. Conclusions and future work

A body of work for the field of astronaut training in VEs was presented. The suitability of VEs utilizing projection technology for astronaut training tasks in zero gravity conditions was investigated. This was accomplished through building a projection technology and PC cluster-based VE platform and a training prototype utilizing this platform. An interaction technique battery was designed and implemented. The demands of this work were based on a document that collected the user requirements based on industrial partner scenarios in the VIEW project. A specific training task—laptop installation in the FSL module of the ISS—was selected and implemented. Preliminary user tests were conducted and the results were evaluated. The results from the user evaluation show that there is a real potential to use such VR systems for astronaut training applications. Although there are some technical limitations with the current set-up, some of these issues can be addressed without waiting for advances in technology. For example, enhancing the menu design and improving the fit of the glove so that the weight of the electronics box does not cause it to twist would improve the response of the system to appropriate gestures. Of particular importance is that a real potential user of this technology—an astronaut—was very positive about its use in astronaut training applications.

As it seems that projection-based VR can be successful in astronaut training, we intend to continue the development of the technologies described in this paper. From the technical development point of view training scenario management needs better tools. This includes enhancements for geometric model import and interactive physical constraint design as well as the development of initial object positioning for the scenario under development. In the field of trainee interaction the navigation methods will need to correspond with the real world behaviour; the astronauts move using handles attached to the walls, ceilings and roofs of the ISS corridors. This requires a more thorough physics-based model of the human operator. Regarding the user testing activities more task sequences are needed to define a significant test to verify effective learning in a training activity. We also have to introduce parameters to increase the real perception of the environment simulating zero gravity environment behaviour conditions. As the technology seems very promising and as it is relatively low cost, we intend to commercialize the VE-View platform and the content production tools.

References

Barfield, W., Baird, K., Bjorneseth, O., 1998. Presence in virtual environments as a function of type of input device and display update rate. Displays 19, 91–98.

Billinghurst, M., 1998. Put that where? Voice and gesture at the graphics interface. Computer Graphics 32 (4), 60–63.

Bowman, D.A., 1999. Interaction techniques for common tasks in immersive virtual environments. Doctoral thesis. Georgia Institute of Technology.

Bowman, D.A., Hodges, L.F., 1997. An evaluation of techniques for grabbing and manipulating remote objects in immersive virtual environments. In: Proceedings of the 1997 Symposium on Interactive 3D Graphics. ACM Press, New York, pp. 35–38.

Burzio, L., Ferrino, M., Masali, M., 2003. Laptop Usability Analysis and Human Centred Design Working in Micorgravity. In: HAAMAHA Eighth, International Conference, 27–30 May, Rome, pp. 361/365.

Connors, M.M., 2001. Living Aloft: Human Requirement for Extended Space Flight, NASA SP 483, April e-Work (2001), Status Report on New Ways to Work in the Knowledge Economy, Information Society Technologies, September (available on line www.eto.org.uk).

Cruz-Neira, C., Sandin, D.J., DeFanti, T.A., 1993. Surround-screen projection-based virtual reality: the design and implementation of the CAVE. ACM Computer Graphics 27 (2), 135–142.

D'Cruz, M.D., 1999. Structured Training in Virtual Environments (STRIVE). Ph.D. Thesis, University of Nottingham.

ESA, 2004. ESA Astronauts Training Programme. Retrieved on June 23rd, 2004 from http://www.esa.int/export/esaHS/ESAVPT0VMOC_astronauts_0.html.

Fakespace, 2004. Fakespace Systems. Retrieved on May 14th, 2004 from http://www.fakespace.com/.

Ferrino, M., 2004. Living in outer space: anthropology and proxemic methods for human adaptation analysis in microgravity environment. Journal Biological Research, Rubbettino–Soveria Mannelli Ed., in print.

Ferrino, M., Gaia, E., 2003. Workplace for the Future: A Multi-Disciplined Approach for Living in Outer Space. In: HAAMAHA Eighth, International Conference, 27–30 May, Rome.

Foley, James, D., Van Dam, A., Feiner Steven, K., Hughes John, F., 1996. Computer Graphics: Principles and Practice in C. Addison-Wesley, Reading.

Kalawsky, Roy. S., 1993. The Science of Virtual Reality and Virtual Environments. Addison-Wesley, Reading.

Kalawsky, R., 1999. VRUSE—a computerised diagnostic tool: for usability evaluation of virtual/synthetic environment systems. Applied Ergonomics 30, 11–25.

Loftin, R.B., Kenney, P., 1995. Training the Hubble space telescope flight team. Computer Graphics and Applications 15 (5), 31–37.

Manzey, D., 2003. Human Missions to Mars: New Psychological challenges and Research Issues. University of Applied Sciences (FH), Faculty of Business Psychology. In: 54th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law, 29 September–3 October, Bremen, Germany.

Masali, Ferrino, 2004. Man adaptability to outer space: a primate model to decode our next step? In: XX Congress International Primatological Society, Turin 23–28 Ago (in print).

Meinster, D., 1986. In: Salvendy (Eds.), Advances in Human Factors/Ergonomics, Human Factors Testing and Evaluation. Elsevier, Amsterdam.

Montgomery, K., Bruyns, C., Wildermuth, S., 2001. A virtual environment for simulated rat dissection: a case study of visualization for astronaut training. In: Proceedings of the Conference on Visualization 2001. IEEE Press, Piscataway, NJ, USA, pp. 509–514.

Oviatt, S., 1999. Ten Myths of multimodal interaction. Communications of the ACM 42 (11), 74–81.

REAL MAN IST-2000-29357, Integrated Technology for Dynamic Simulation and Advanced Visualisation of Human Motion in Virtual Environment: EU Project.

Rönkkö, J., 2004. Game technology in virtual reality development. Ercim News 57, 40–42.

Rönkkö, J., Launonen, R., Laukkanen, S., Gaia, E., 2003. Multimodal interaction techniques for astronaut training in virtual environments. In: Second International Conference on Universal Access in Human–Computer Interaction. Crete, Greece, 22–27 June 2003 Human–Computer Interaction Theory and Practice (Part I). Lawrence Erlbaum Associates, London, pp. 1238–1242.

VIEW, 2003. Virtual and Interactive Environments for Workplaces of the Future. Retrieved February 10, 2003 from http://www.view.iao.fhg.de.

Zachmann, G., 2000. Virtual Reality in Assembly Simulation—Collision Detection, Simulation Algorithms and Interaction Techniques. Doctoral Dissertation. University of Darmstadt.