THE VIRTUAL GLOVEBOX: EMERGING SIMULATION TECHNOLOGY FOR SPACE STATION EXPERIMENT DESIGN, DEVELOPMENT, TRAINING AND TROUBLESHOOTING

Jeffrey D. Smith[*†], I. Alexander Twombly[†], A. Christopher Maese[*], Yvonne Cagle[§], Richard Boyle[*]

[*]NASA Ames Research Center, Moffett Field, CA 94035
[†]University Space Research Association, Moffett Field, CA 94035
[§]NASA Johnson Space Center, Houston TX 77058

ABSTRACT

The International Space Station demonstrates the greatest capabilities of human ingenuity, international cooperation and technology development. The complexity of this space structure is unprecedented; and training astronaut crews to maintain all its systems, as well as perform a multitude of research experiments, requires the most advanced training tools and techniques. Computer simulation and virtual environments are currently used by astronauts to train for robotic arm manipulations and extravehicular activities; but now, with the latest computer technologies and recent successes in areas of medical simulation, the capability exists to train astronauts for more hands-on research tasks using immersive virtual environments. We have developed a new technology, the Virtual Glovebox (VGX), for simulation of experimental tasks that astronauts will perform aboard the Space Station. The VGX may also be used by crew support teams for design of experiments, testing equipment integration capability and optimizing the procedures astronauts will use. This is done through the 3D, desk-top sized, reach-in virtual environment that can simulate the microgravity environment in space. Additional features of the VGX allow for networking multiple users over the internet and operation of tele-robotic devices through an intuitive user interface. Although the system was developed for astronaut training and assisting support crews, Earth-bound applications, many emphasizing homeland security, have also been identified. Examples include training experts to handle hazardous biological and/or chemical agents in a safe simulation, operation of tele-robotic systems for assessing and diffusing threats such as bombs, and providing remote medical assistance to field personnel through a collaborative virtual environment. Thus, the emerging VGX simulation technology, while developed for space-based applications, can serve a dual use facilitating homeland security here on Earth.

INTRODUCTION

The era of the International Space Station (ISS) has finally arrived, providing researchers on Earth a unique opportunity to study long-term effects of weightlessness and the space environment on structures, materials and living systems. Many of the physical, biological and material science experiments planned for ISS will require significant input and expertise from astronauts who must conduct the research, follow complicated assay procedures and collect data and samples in space. Containment is essential for much of this work, both to protect astronauts from potentially harmful biological, chemical or material elements in the experiments as well as to protect the experiments from contamination by air-borne particles in the Space Station environment. When astronauts must open the hardware containing such experiments, glovebox facilities provide the necessary barrier between astronaut and experiment.

On Earth, astronauts are faced with the demanding task of preparing for the many glovebox experiments they will perform in space. Only a short time can be devoted to training for each experimental task and glovebox research only accounts for a small portion of overall training and mission objectives on any particular ISS mission. The quality of the research also must remain very high, requiring very detailed experience and knowledge of instrumentation, biology and specific scientific objectives for those who will conduct the research. Furthermore, for astronauts to

be successful space-based scientists they must remain highly proficient in a wide variety of specific research tasks. However, due to scheduling constraints, they can receive only limited Earth-based training with real glovebox mock-ups and real experimental specimens. Finally, this Earth-based training may occur months prior to the mission and astronauts can never fully practice these procedures under the microgravity conditions they will face in space. These challenges place very high requirements on astronaut crews and the support teams who must train the astronauts quickly and accurately with very little room for error.

This unique set of needs faced by NASA has inspired the development of a new computer simulation tool, the Virtual Glovebox (VGX), which is designed to provide astronaut crews and support personnel with a means to quickly and accurately prepare and train for glovebox experiments in space. The VGX is a semi-immersive virtual environment with computer software simulation, useful for engineering development, experiment planning and advanced glovebox training activities. It can be used to streamline these processes at NASA and reduce the need for full-scale training sessions with physical mock-ups or provide astronauts with an efficient, interactive means to keep their skills sharp while on Earth. The VGX software also runs on affordable PC-based computer systems which brings training opportunities to astronauts rather than requiring astronauts to go to training opportunities. A software version of the VGX could also be made robust enough to be taken aboard the Space Station, giving astronauts a final chance to practice complex experiments just before performing the actual procedures in space.

BACKGROUND

Virtual Environment Simulation

Today, the terms "virtual reality" and "virtual environment" are commonly associated with high-speed computer workstations and high-resolution graphics capabilities, which can deliver a virtually real simulation of a real-world event. These computer-based training systems, however, have their roots in the aviation industry and predate any computer. The concept began in 1929 when Edwin A. Link, a pilot and inventor, created the first flight simulator which was adopted in 1934 by the Army Air Corps and later used extensively to train pilots during World War II[1]. The modern flight simulator combines computer generated imagery with real cockpit controls on a motion platform[2]. Flight simulators of this type are the most common and successful example of virtual reality being used to train professionals for real-world tasks.

Virtual environment training is also used by astronauts to train for a number of space-based research tasks[3]. At NASA Johnson Space Center, head mounted display systems, hand-tracking gloves and computer simulation systems are used to train mission specialists for Extra Vehicular Activities (EVA) and robotic arm manipulations required aboard Shuttle and the ISS. Astronauts have also used computer-based tools while in space. They have used expert systems to help them set up complex experiment equipment during sleep studies[4]. In addition, they have used imaging technologies and tracking gloves to test their reaction times in space[5].

The key to success for existing computer-based simulators used by pilots and astronauts is in the way they combine a simulated external environment with real cockpit control systems such as joy sticks, buttons, displays and warning signals. This provides a human-computer interface that is exactly like the human-machine interface of the real aircraft or space system. It is a much more challenging task to develop successful human-computer interfaces for simulations systems in which an operator has a direct hands-on interaction with the physical world.
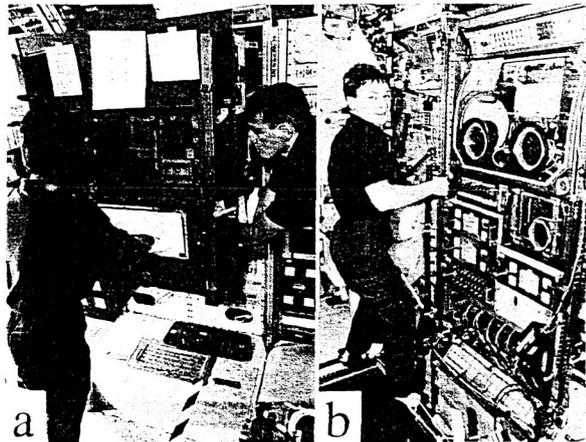
Medical simulators which use specially-designed force-feedback and tracking devices, have recently come into use and promise to duplicate the success of the flight simulator for medical evaluation and surgical training tasks[6,7]. Today, "the Holy Grail for the surgical education community would be a valid, reliable, and sensitive measuring system, easily administered, allowing for the preemptive evaluation of residency candidates, and providing analysis of a given resident's progress throughout his or her training."[8] Toward this goal, virtual environment simulations are starting to move into the medical mainstream (for a recent review see reference 6); but, due to their very recent introduction, evaluations of these systems have not yet demonstrated the full potential of simulation as an indispensable medical training tool.[9-11]

Although their jobs are very different, surgeons, pilots and astronauts share the same kind of responsibilities. They all face constantly changing conditions and must make potentially life-threatening decisions quickly and sometimes in rapid succession. Flight simulators have been so useful because of their ability to expose pilots to life-threatening virtual environments without any real risk. Current space simulators have been successful by focusing on external space operations like robotic arm manipulation and EVA. Medical simulators, however, require a realistic hands-on human-computer interface. As this technology matures, it will begin to provide the same kind of successful training experience for surgeons and medical students as flight/space

simulators have provided for pilots, flight students and astronauts for many years. In order to train astronauts for tasks they must perform inside the Shuttle or Space Station, the technologies developed by the hands-on medical simulators must be combined with the training expertise of flight and space simulators.

Space-based Glovebox Systems

The use of the glovebox as an isolation system for space-based research is not new. Gloveboxes of various sizes and capabilities have flown as payloads on a number of Shuttle science missions. The General Purpose Work Station (GPWS) is an example of one of the larger glovebox systems used by astronauts aboard the Shuttle (Figure 1-a). This glovebox system last flew in the Spaclab science module aboard the Shuttle Columbia on STS-90, April 17 to May 3, 1998. During this flight, the "Neurolab" mission, astronauts performed numerous experiments to further understand space adaptation syndrome (space sickness), neurophysiology in space, balance organs and the development/response of the nervous system in small fish and invertebrates in microgravity. Many of these experiments required one or two astronauts working in the GPWS to open sample containers, process biological specimens and collect scientific data. Today, the Destiny Lab module of the International Space Station houses one of the most sophisticated glovebox facilities yet to fly in space. The Microgravity Sciences Glovebox (MSG) is currently being used for a series of materials science, micro-physics and bio-processing experiments (Figure 1-b). The MSG has an enclosed
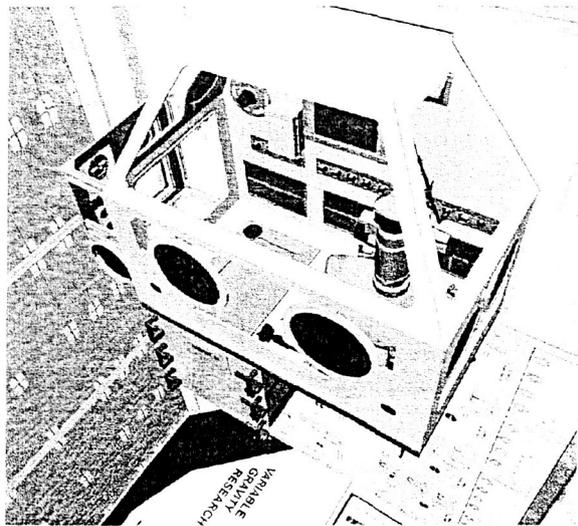
volume of 255 liters and a floor space about 80 cm wide by 60 cm deep.[12]

For tasks requiring a larger work volume, the Life Sciences Glovebox Facility (LSG) will be used. When delivered to the Space Station several years from now, the LSG will be the largest, most complex glovebox system ever in space. Glove ports on two sides let up to two astronauts work simultaneously in the LSG which has a containment volume of nearly half a cubic meter and a floor space about 100 cm wide and 60 cm deep. When extended from the Space Station rack in its deployed position, as shown in Figure 2, the LSG will provide the crew with a pull-out workbench for performing biology experiments in space[13]. It is equipped with holding racks and an air-lock attachment for contained specimen transfer. A suite of experiment-unique equipment and supplies have been developed that take into account the microgravity environment in space and the unique constraints imposed on the astronauts both from environmental restrictions and through the glovebox interface.

Astronaut Training for Glovebox Experiments in Space

Today, astronauts prepare for life science experiments through a series of training videos, visits with scientists and practice experiments using Earth-based mock-ups and real biological specimens. The opportunities for these full-scale mock experiments are rare and, due to the heavy work-loads astronauts face when preparing for their missions, it may be weeks or months between their last practice experiment and the

Figure 1. a) Chiaki Naito-Mukai, alternate payload specialist, and astronaut Richard M. Linnehan, mission specialist, practice during crew training in the General Purpose Work Station (GPWS). b) Astronaut Peggy A. Whitson, Expedition Five flight engineer, works near the Microgravity Science Glovebox (MSG) in the Destiny laboratory on the International Space Station.

Figure 2. CAD model of the Life Sciences Glovebox Facility (LSG). The system is shown in its deployed configuration aboard the ISS. An air-lock module is attached on the side of the LSG and a habitat module is attached below.

actual procedure performed in space. Developing crew training requirements for specific payloads is a significant challenge, and making training efficient is essential to provide focus on safety and research objectives. Technologies like the VGX will build on the current training schedules of astronauts and promise to reduce required training time and the number of live specimens required for preparatory experiments.[14]

VIRTUAL GLOVEBOX SYSTEM DESCRIPTION

The Virtual Glovebox (VGX) is a new technology, designed for simulation of experimental tasks that astronauts will perform aboard the Space Station. The VGX may also be used by crew support teams for design of experiments, testing equipment integration capability and optimizing the procedures astronauts will use. This is done through the 3D, desk-top sized, reach-in virtual environment that can simulate the microgravity environment in space. Additional features of the VGX allow for networking multiple users over the internet and operation of tele-robotic devices through an intuitive user interface.

A unique Stereoscopic Display Station is used to provide an immersive virtual environment for the VGX simulation software. Dual EPSON™ LCD projectors with circular polarization filters provide high resolution images in stereo at frame rates of 60 Hz per eye (Figure 3). The current image resolution is 1280 pixels wide by 1024 pixels high projected onto a screen 100 cm wide and 80 cm in height for an effective dot size of 1.28 pixels per millimeter. To minimize the space required for projection, the throw distance from projector to screen is short (about 2 meters) and reflects off a mirror mounted above the workspace. The image projected into the VGX falls on a flat screen which is above the user's arms. The user looks down into the Display Station, onto the front-projected screen (Figure 4). With the use of light-weight circularly polarized stereo glasses, a 3D virtual environment 100 cm wide, 75 cm deep and 60 cm in height is created for user interaction. This internal working space of the Stereoscopic Display Station is almost identical to the space inside the LSG.

Stereo display is achieved by creating a virtual display space on a dual-output graphics card (using the nVidia Quadro4 graphics chipset), implemented in OpenGL. This display space is achieved through two components: 1) a mapping of the left- and right-eye view that can be displayed through the dual output system of the graphics board, and 2) a viewpoint tracking system used to create the viewport mapping for each eye to the display. The mapping of the left- and right-eye views to the dual output of the graphics card requires architecture different from that typically used in OpenGL stereo display systems.[15]

On the desktop inside the VGX, a scientist,
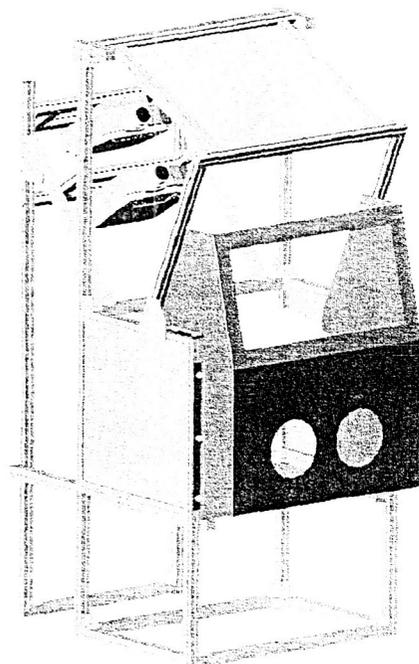
Figure 3: *CAD model of the Virtual Glovebox Stereoscopic Display Station which is constructed from plastic and aluminum. Two LCD projectors reflect off a mirror onto a silvered screen to provide stereo imaging capabilities.*

Projectors — Mirror

Flat Screen
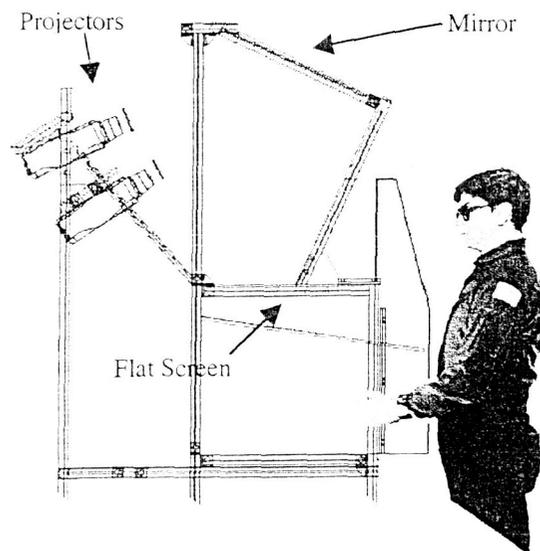
Figure 4: *Side view showing the Virtual Glovebox user interface. The user reaches into the workspace below a flat viewing screen allowing for a representation of virtual hands to be shown on the screen between the user's eyes and hands.*

astronaut or technician can interact with virtual objects through a pair of Cybergloves® (Immersion Inc.) that are tracked in the computerized virtual environment using a Flock-of-Birds® magnetic tracking system (Ascension Technology Inc.). The operator inserts his/her hands through the front arm-holes of the box and into the gloves which are connected to the PC computer control system running the virtual environment simulation (Figure 5). Virtual representations of the user's hands are shown on the viewing screen in the box and overlaid with the real position of each hand. The VGX allows for a single operator working through the front physical interface; however, future hardware and software developments will allow for additional users to enter via network connections to work simultaneously with the first operator or to observe and advise.

Custom software, incorporating elements of modeling, simulation and training into an intuitive virtual environment user interface, is being developed for VGX experiment simulation. As the design and development of the LSG Facility are completed, accurate 3D models of the LSG and associated equipment must be incorporated into the simulation system. A physically-based simulation which controls objects in the virtual workspace of the VGX has been built upon the Arachi Dynamics Engine (Arachi Inc.), a C++ library of functions for governing object geometry, collisions, dynamics, and force accumulation.[16] Peripheral devices are integrated into the simulation loop via callbacks to the devices that update data structures in the simulation system. Communication with peripheral devices is accomplished with standard C++ library functions provided by the manufacturers. A basic schematic of the Arachi-based simulation loop
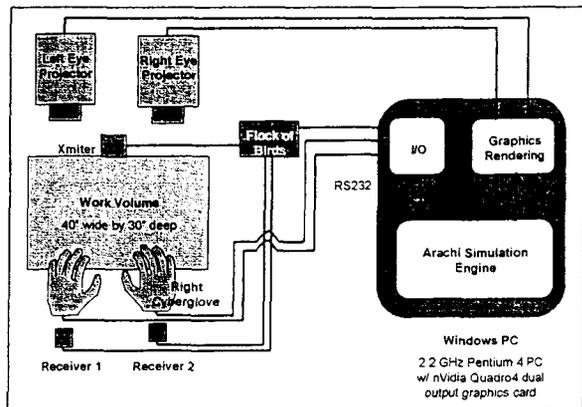

Figure 5. *Virtual Glovebox System Design incorporates off-the-shelf tracking devices in a virtual work volume displayed by duel-LCD projectors. The system is run by a single PC running the Arachi Simulation Engine.*

is shown in Figure 6. Medical simulation tools based on the "Spring" simulation engine have also been adapted for use in the Virtual Glovebox.[15,17] Geometric models used in the VGX have been created with Computer Aided Design (CAD) tools and reflect the most current state of the LSG design (CITE ISSUTIL OR CCCT). As adjustments are made to the LSG hardware, the 3D models for the VGX can also be modified.
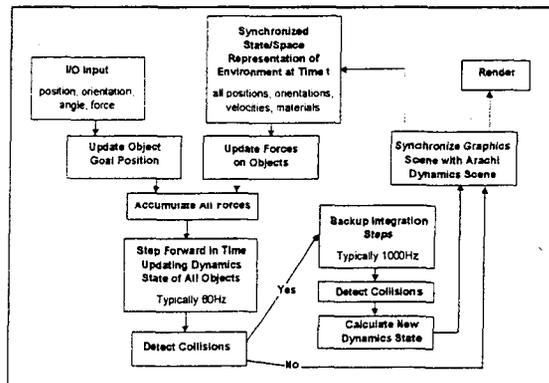

Figure 6. *The Arachi Simulation Engine follows a physically-based modeling simulation loop. Input from peripheral devices is incorporated into the dynamic state of objects. Collisions are handled and the forces on objects are summed at 60Hz to provide real-time rendering of visual objects in the virtual environment.*

SPACE APPLICATIONS

The Virtual Glovebox was designed and developed for experimental design for on-orbit biological research and simulation for training astronauts to perform biological experiments in space.

Experimental Design for On-Orbit Research

The VGX provides a powerful experimental design and optimization tool for the LSG. In the VGX environment, an operations technician can quickly organize or rearrange virtual supplies, biological specimens or experiment equipment and test a variety of experimental procedures. Gravity can be turned off in the VGX, allowing a designer to optimize the experimental procedure for the microgravity conditions astronauts will face in space rather than designing for the nominal 1-g environment on Earth. This work may be initiated on a regular desktop PC (Figure 7) and then moved into the semi-immersive Virtual Glovebox for testing and final evaluation. Thus, efficient experimental protocols can be quickly developed and tested by operations technicians without the need for real equipment mock-ups or biological

specimens. This will shorten the experimental design process and produce better procedures for research in space.

Simulation and Training for Experiments in Space

The over-arching design goal of the VGX is to provide a realistic virtual environment simulation system to train astronauts to conduct complex biological research in space. The user interface employs state-of-the-art graphics, haptics and tracking devices to provide an unparalleled level of realism to a user working in the virtual environment. An astronaut who has seen the LSG and has performed related biological experiments on Earth (a skilled user) will be able to approach the VGX, put on tracking gloves and 3D glasses and then reach into the box to interact with the virtual environment in much the same way that he or she would do in a real LSG mock-up (Figure 8). The astronaut will still require minimal training in the proper use of the virtual reality display and equipment; however, future improvements in the user interface may eliminate the need for cumbersome magnetic tracking devices which are tethered to computers by wires, thus, incrementally improving the intuitive interface.


Figure 7. A technician tests a procedure developed for the Virtual Glovebox using a keyboard and mouse interface on a desktop PC workstation. Objects are placed in the environment and procedural steps are defined. Then a simulation is used to test the equipment configuration and procedure.

HOMELAND SECURITY

Although the VGX was developed for astronaut training and assisting support crews, Earth-bound applications also exist, many of which emphasize homeland security. Virtual environment systems can be used for training, collaboration and for tele-presence activities. These utilities make the VGX an excellent tool for NASA, but they also make the system desirable for applications here on Earth.
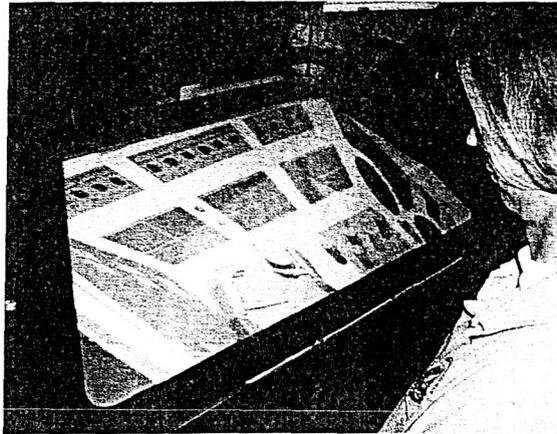
Figure 8.   Immersive simulation in the Virtual Glovebox. A user manipulates objects in the virtual environment. The virtual hands are controlled through Cybergloves worn by the operator. The operator looks down on the screen to perceive a three-dimensional workspace with his/her real hands in the same relative positions as those of the virtual hands.

Training: Proper, Efficient and Timely

Astronaut training focuses on the proper, efficient and timely delivery of information and skills to the astronaut crews. The VGX is designed to streamline this process for some of the world's most highly educated and highly trained experts. There are numerous applications on Earth where highly educated, highly trained experts need to acquire new skills or a refresher to keep skills sharp. The VGX may be used to train medical or biological professionals in tasks that can be performed in a desktop-sized work area no larger than the glovebox workspace. The most obvious application is in hazardous chemical or bio-weapons handling, which would normally be carried out in a glovebox or similar isolation system. Some advantages of using a virtual environment training system over conventional physical mock-ups include 1) the ability to graphically represent something that would normally not be seen such as a radioactive chemical, aerosolized virulent particles, or contamination, 2) the ability to train on a variety of scenarios in quick succession with no set-up/tear down time and 3) a quantitative analysis of performance including error messages during simulation (Figure 9) and data such as completion time and probability of success. Other applications in

medical/biological fields may include the preparation of reagents or antidotes, administration of emergency aid or practicing bio-clean-up procedures.

Collaboration: Multiple Users Working Together in the Same Virtual Environment

Important network collaboration aspects of the VGX will allow astronauts, based at Johnson Space Center in Houston, Texas to interact in real-time with experiment training crews at Ames Research Center in Moffett Field, California. The hands-on nature of the virtual environment provided by the VGX will improve these distance-learning sessions. Today, there are relatively few experts in many areas of homeland security, for example, bio-weapons identification, bomb diffusion, and hazardous waste clean up. Making these experts available for training or bringing them immediately to the site of an incident is not always possible. A collaborative virtual environment provided by a virtual glovebox could enhance normal training activities by allowing top experts to participate in hands-on training sessions with students who may be thousands of miles away. A VGX could also be used by experts, located hours away by air, to quickly give hands-on instruction to local personnel who must immediately deal with a new threat or incident in their area.

Tele-Presence: Safety, Accuracy and Access

Virtual environment systems are very useful for immersing a human operator of a robotic system into a hazardous or physically impossible location. Robotic
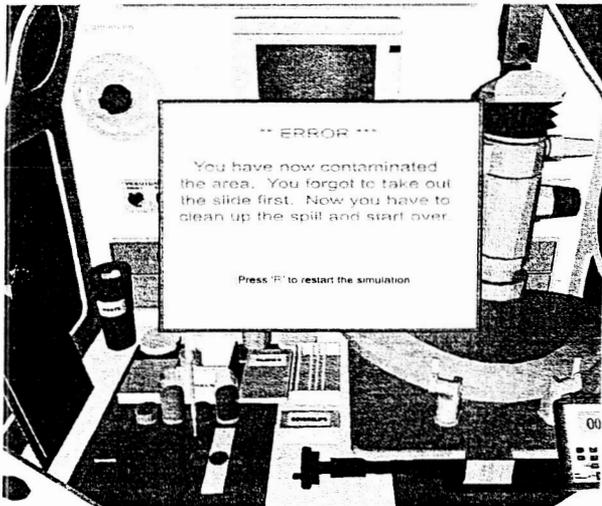
Figure 9. Error message provides immediate feedback for training and evaluation. This error message appears when the operator contaminates a bio-sample which was being processed for microscopic analysis in the simulated procedure.

systems are becoming increasingly more humanoid in appearance and function. For example, the Robonaut, developed by NASA Johnson Space Center, has a head, arms and hands to work out in the vacuum of space while a human operator controls its systems from a much safer position inside the Space Station.[18] The virtual environment in the VGX could be used to provide a more intuitive human-computer interface for humanoid robots such as Robonaut. The VGX could also be used as an intuitive controller for Earth-based robots that enter hazardous areas such as fire, chemical spills, unstable debris, unexploded ordinance or into enemy fire. The tele-presence provided by an immersive virtual environment gives a human operator improved situational awareness over conventional interfaces such as a joystick or keyboard. This leads to better performance and lower training requirements for operating these robotic systems.

CONCLUSIONS

Many of the most fundamental biological questions concerning life's ability to adapt and respond to the space environment are still unanswered. The Life Sciences Glovebox Facility is a containment barrier system that will be placed aboard the ISS and used by astronauts while performing this ground-breaking biological research in space. The Virtual Glovebox is a new virtual environment technology, designed to provide a realistic LSG training experience for astronauts without many of the time-consuming requirements of biology research training using real mock-ups and specimens.

The VGX sets a new precedent for high-fidelity virtual environment training tools by combining ultra-high resolution computer graphics with magnetic tracking and haptic feedback devices in an immersive desktop environment. This provides an unparalleled level of realism to a user who can intuitively perform experimental tasks in a real-time microgravity or nominal 1-g simulation. Determining operational efficiencies for LSG equipment, optimal experimental design and simulation for training and evaluating operator performance are all VGX applications that will streamline processes associated with performing biology research in space.

Earth-based applications, many emphasizing Homeland Security have also been identified. Examples include training experts to handle hazardous biological and/or chemical agents in a safe simulation, operation of tele-robotic systems for assessing and diffusing threats such as bombs, and providing remote medical assistance to field personnel through a collaborative virtual environment. Thus, the emerging

VGX simulation technology, while developed for space-based applications, can serve a dual-use facilitating homeland security and other professional training and development applications here on Earth.

ACKNOWLEDGEMENT

REFERENCES

1. Allen, L. D., "Evolution of Flight Simulation," AIAA Paper 93-3545-CP, Aug. 1993.

2. Aviation Systems Division, Vertical Motion Simulator, NASA Ames Research Center, Moffett Field CA, http://www.simlabs.arc.nasa.gov/vms/vms.html.

3. Savage, P. D., and Smith, J. D., "Utilization of Virtual Environments for Astronaut Crew Training," *SAE Technical Paper Series*, 2000-01-2361, July 2000.

4. Callini, G., Essig, S. M., Heher, D. M., and Young, L. R., "Effectiveness of an Expert System for Astronaut Assistance on a Sleep Experiment" *Aviation Space and Environmental Medicine*, Vol. 71, No. 10, 2000, pp. 1023-32.

5. Fowler, B., Bock, O., and Comfort, D. "Is Dual-Task Performance Necessarily Impaired in Space?" *Human Factors*, Vol. 42, No. 2, 2000, pp. 318-326.

6. Satava, R. M., "Accomplishments and Challenges of Surgical Simulation," *Surgical Endoscopy*, Vol. 15, No. 3, 2001, pp. 232-241.

7. Satava, R. M., and Jones, S. B., "Virtual Environments for Medical Training and Education," *Presence*, Vol. 6, No. 2, 1996, pp. 139-146.

8. Gorman, P. J., Meier, A. H., Rawn, C., and Krummel, T. M., "The Future of Medical Education is no Longer Blood and Guts, it is Bits and Bytes," *American Journal of Surgery*, Vol. 180, No. 5, 2000, pp. 353-356.

9. Grantcharov, T. P., Rosenberg, J., Pahle, E., and Funch-Jensen, P., "Virtual Reality Computer Simulation," *Surgical Endoscopy,*. Vol. 15, No. 3, 2001, pp. 242-244.

10. Rosen, J., and Hannaford, B., "Markov Modeling of Minimally Invasive Surgery Based on Tool/Tissue Interaction and Force/Torque Signatures for Evaluating Surgical Skills," *IEEE Transactions on Biomedical Engineering,* Vol. 48, No. 5, 2001, pp. 579-591.

11. Tracey, M. R., and Lathan, C., E., "The Interaction of Spatial Ability and Motor Learning in the Transfer of Training from a Simulator to a Real Task," *Stud. Health Technol. Inform.*, Vol. 81, 2001, pp. 521-527.

12. Baugher, C., "The Microgravity Science Glovebox," *AIAA Conference on International Space Station Utilization*, Kennedy Space Center, FL, October 15-18, 2001, (AIAA paper 2001-5089).

13. Santos, O., Meeker, G. and Hing, S., "The Space Station Biological Research Project: Mission, Goals, and Status," *AIAA Conference on International Space Station Utilization*, Kennedy Space Center, FL, October 15-18, 2001, (AIAA paper 2001-4983).

14. Smith, J. D., Twombly, I. A., Bruyns, C. and Boyle, R., "NASA Virtual GloveboX (VGX): Training and Simulation for Biology Research Aboard the International Space Station," *AIAA Conference on International Space Station Utilization*, Kennedy Space Center, FL, October 15-18, 2001, (AIAA paper 2001-5105).

15. Twombly, I. A., Smith, J. D., Bruyns, C., Montgomery, K. and Boyle, R., "NASA Virtual GloveboX: an immersive virtual desktop environment for training astronauts in life science experiments," *Proceedings of the Seventh Multi-Conference on Systemics, Cybernetics and Informatics*, Vol. V, Jul. 27-30, 2003, Orlando, Florida, pp. 487-92.

16. Smith, J. D., Twombly, I. A., Ruspini, D. and Boyle, R., "Real-time Physically-based Simulation in a Virtual Glovebox for Training Astronauts to Perform Research Tasks in Space," *Proceedings of the International Conference on Computer, Communication and Control Technologies*, Vol. IV, Jul. 31 – Aug 2, 2003, Orlando FL, pp. 385-91.

17. Montgomery, K., Bruyns, C., Brown, J., Thonier, G., Tellier, A. and Latombe, J. C., "Spring: A General Framework for Collaborative, Real-Time Surgical Simulation", *Medicine Meets Virtual Reality (MMVR02)*, Newport Beach, CA, January 23-26, 2002.

18. Ambrose, R., Culbert, C. and Rehnmark, F., "An experimental investigation of dexterous robots using EVA tools and interfaces," *AIAA Space 2001 – Conference and Exposition*, Albuquerque, NM, Aug. 28-30, 2001 (AIAA paper 2001-4593).