603970

The Virtual Glovebox (VGX): an Immersive Simulation System for Training Astronauts to Perform Glovebox Experiments in Space

By: Jeffrey D. Smith
Space Life Sciences Research Branch
NASA Ames Research Center
Moffett Field, CA

Email: jdsmith@mail.arc.nasa.gov

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-born 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, anatomy 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 stemmed 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. The system integrates consumer software and hardware with custom real-time simulation technologies to provide a realistic 3-D virtual environment mimicking a real glovebox environment. With the VGX, gravity can be turned off, allowing astronauts to perform experiments in a simulated microgravity environment while still on Earth. The VGX does not eliminate the need for Space Station Glovebox training and experiment planning using physical mock-ups and live specimens. Instead, it can streamline these processes, reduce the need for full-scale training sessions with live animals and provide astronauts with a means to keep their skills sharp on Earth and on the Space Station, thereby maximizing the efficiency and success of ground-breaking biological experiments in space. With additional development, the VGX software simulation may be ported to small, affordable PC-based computer systems to bring training opportunities to astronauts rather than requiring astronauts to go to training opportunities This smaller 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

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 its 25th flight, 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 [1].

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 [2]. 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. 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. Astronauts who must perform LSG experiments in space are faced with achieving a very high level of proficiency on a suite of complex hardware with very little time to train. In addition, the inherent complexity of biology research increases the need for highly skilled and experienced operators. With that, the need for high-fidelity computer-based training using the Virtual Glovebox becomes the best means to augment current training activities and streamline the process for both astronauts and support teams.

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 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 [3].

VIRTUAL GLOVEBOX SYSTEM DESCRIPTION

The VGX is a state-of-the-art virtual environment technology which sets new standards for speed, resolution and desktop user-interface immersion. Unlike any commercial product or research prototype before it, the VGX is designed to combine real-time graphics, haptics and tracking in an immersive photo-realistic desktop environment which can provide a user with unparalleled realism for their virtual tasks. The VGX hardware and software were assembled specifically for engineering development, experimental design and astronaut training for the Space Station Life Sciences Glovebox Facility. Nevertheless, its versatility allows for adaptation to other virtual environment simulations and training that are performed in a desktop-sized volume.

A unique Stereoscopic Display Station is used to provide an immersive virtual environment for the VGX simulation software [4]. The initial configuration of the system utilized two high-end CRT projectors with circular polarization options to provide high resolution images in stereo at frame rates of at least 60 Hz per eye (Figure 3). These projectors have since been replaced with smaller, brighter LCD projectors that produce a comparable pixel resolution and increased sharpness over the CRT projectors. 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 3-D 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 which will fly aboard the International Space Station.

On the desktop inside the VGX, a scientist, astronaut or technician can interact with virtual objects through a pair of Cybergloves® (Immersion Inc.) that are tracked in the computerized virtual environment using magnetic trackers (Ascension Technology Inc.). The operator inserts his/her hands through the front arm holes of the box and into the gloves. A virtual representation of the user's hands are shown on the viewing screen in the box and are overlaid with the real position of the user's hands. Two Desktop Phantom™ force feedback devices (SensAble Technologies Inc.) provide a three-degree-of-freedom haptic interface to the user. Virtual tools in the environment that require force feedback for their proper use (e. g. cutting, poking, pinching tools) are overlaid with the Phantom device and can be picked up by the user. 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 is completed, accurate 3-D models of the LSG and associated equipment must be incorporated into the simulation system. A number of models have been built with Computer Aided Design (CAD) tools and reflect the most current state of the LSG design (Figure 5). As adjustments are made to the LSG hardware, the 3-D models for the VGX can also be modified. A second important component of the VGX software, its simulation engine, borrows heavily from physically-based modeling tools and medical simulation tools [5]. The third component of the VGX software will also borrow from medical training tools, but it must have a customized interface specific to astronaut training needs. Astronauts and space operations technicians must be able to move equipment and supplies in and out of the VGX easily. They must be able to start and stop pre-set simulations quickly and also provide feedback for performance evaluation and continued software development. Finally, the user interface for the VGX must be intuitive or it will not be useful as a realistic training tool. The current interface, using off-the-shelf virtual reality tracking and force-feedback systems has cumbersome elements such as wired gloves, tethered magnetic trackers and armatures inside the workspace. Further research will help reduce the need for encumbered interface devices and increase the value of the VGX as a virtual environment training tool.

VIRTUAL GLOVEBOX APPLICATIONS

The Virtual Glovebox was designed and developed for three main applications: engineering evaluation of operational efficiencies for glovebox equipment, experimental design for on-orbit biological research and simulation for training astronauts to perform biological experiments in space.

Evaluation of Operational Efficiencies

The Life Sciences Glovebox Facility is a complex containment system and environment for scientific experiments that require biological specimens and/or hazardous materials aboard the Space Station. Engineers must build experiment-specific equipment and supplies for each research task. This may involve modification of off-the-shelf hardware (microscopes for example) or the creation of completely new systems such as the Mass Measuring Device whose counterpart on Earth, the scale, cannot work in the microgravity of space. In every case, this new equipment must properly interface with the LSG. Also, the equipment and tools cannot interfere with each other and they must be easily accessible during experiments when they are required. The Virtual Glovebox allows engineers a means to place tools and equipment in the LSG, try a variety of positions, orientations and attachment points for the equipment and even test a number of prototype designs without actually having to build or manipulate the physical hardware. Many virtual tools and LSG equipment are already available for the VGX (Figure 6). The ability to add/remove and arrange LSG equipment and tools in a virtual environment will allow for fast and easy assessment of optimal equipment configurations and use of the limited space within the LSG.

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. 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 for ground-breaking 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 3-D 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. 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.

Realism of user experience is part of the VGX advantage. Virtual objects must float, fall and tumble correctly in the simulated gravity or microgravity environment. Rigid objects must collide with one another and if they normally connect/disconnect or are hinged (*e.g.* vials with caps, boxes with lids or scissors) then they must interface and move in the same way as their real counterparts. Additionally, soft objects, most notably biological tissues and specimens, must deform realistically when touched, cut or allowed to float under simulated microgravity conditions. Many of these requirements for the VGX parallel those already found in surgical simulation software. Thus, the physically-based processes and interactions between objects which are needed for the VGX are all accurately modeled using surgical simulation software tools [6].

All virtual environment simulators intended for training purposes need accurate methods for measuring user performance and also for evaluating the quality of skill transfer from virtual task to real-world task. Human-in-the-loop studies with skilled technicians or astronauts as test subjects will be used to evaluate user performance and task transfer to the real procedures performed in the LSG mock-up. Many equipment handling and operation tasks in the LSG are logically similar to those performed by pilots or air traffic control professionals. Therefore, human performance modeling systems used by the aerospace industry are also being applied to the VGX to computationally evaluate LSG procedures and optimize them for experiment success [7] In this way, a combination of evaluation methods for the VGX, borrowed from both medical and aerospace industries, will yield optimal LSG procedures and the best virtual environment training system for astronauts who will use this equipment aboard the International Space Station.

CONCLUSIONS

As the construction phase of the International Space Station nears completion, it will transition from a habited orbital outpost to a fully functional field research station in space. 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. In this way, the NASA VGX may advance existing LSG experiment planning, operations, training and task optimization for astronauts and support crews, thus, helping to maximize the scientific return gained from future biological research in space.

REFERENCES

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

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

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

4. Smith, J., Twombly, I., Bruyns, C., Wildermuth, S. and Boyle, R. (2001) 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 (AIAA paper 2001-5105).

5. Montgomery, K., Bruyns, C., Brown, J., Sorkin, S., Mazzella, F., Tonier, G., Tellier, A., Lerman, B. and Menon, A. (2002) Spring: a General Framework for Collaborative, Real-time Surgical Simulation. *Medicine Meets Virtual Reality*, Vol. 85, pp. 296-303.

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

7. Smith, J., Gore, B., Delal. K. and Boyle, R. (2002) Optimizing Biology Research Tasks in Space Using Human Performance Modeling and Virtual Reality Simulation Systems Here on Earth. *32nd International Conference on Environmental Systems (ICES),* San Antonio, TX, July 15-18 (SAE Technical Paper Series, 2002-02-2500) .

FIGURE LEGENDS

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. Engineering model of the Life Sciences Glovebox Facility (LSG) with air-lock module attached on the side.

Figure 3. a) Stereoscopoic Display Station diagram and b) prototype Virtual Glovebox system.

Figure 4. Operator reaching under the projected screen to see a virtual representation of his hands and the inside of the glovebox.

Figure 5. 3-D models are created from hardware design models, photographs or from actual physical equipment.

Figure 6. Models are created from LSG equipment: a) microscope, b) small-mass-measuring device, c) plant pollination kit, d) common lab tools.

Figure 2

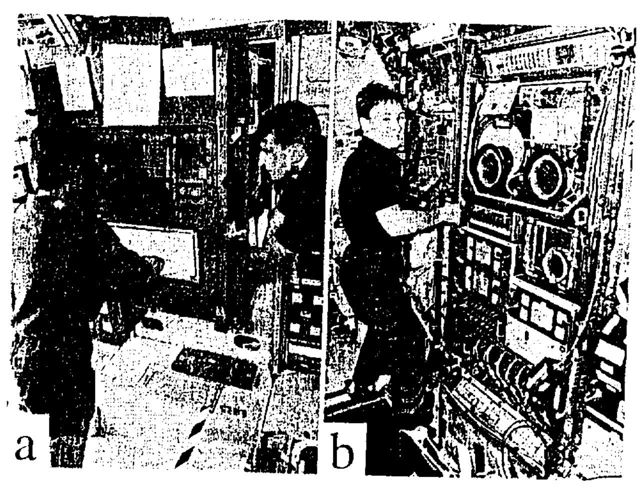


Figure 2

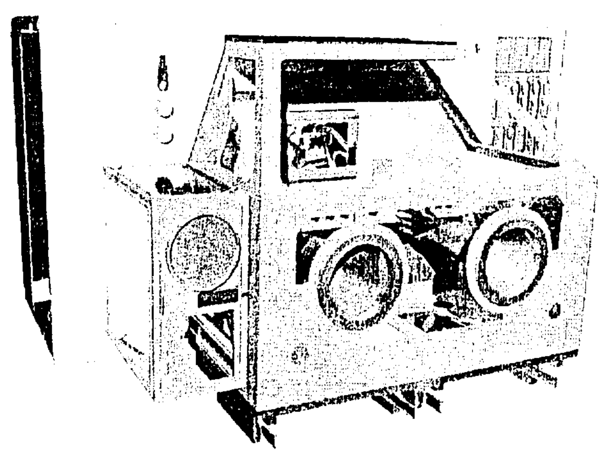


Figure 3

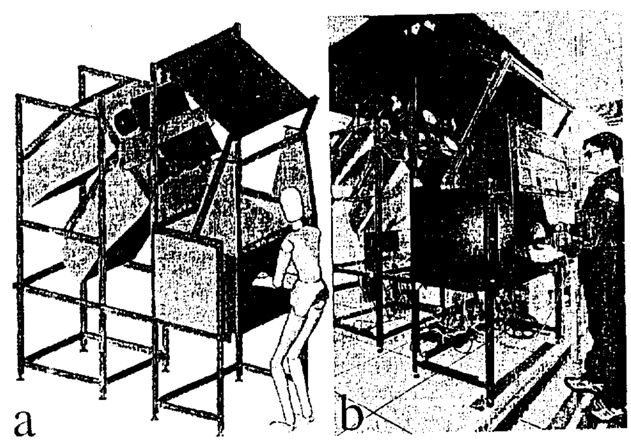
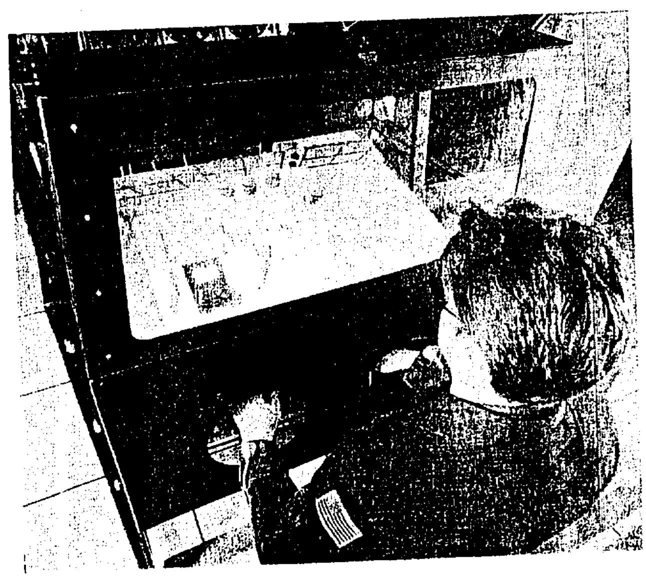


Figure 4



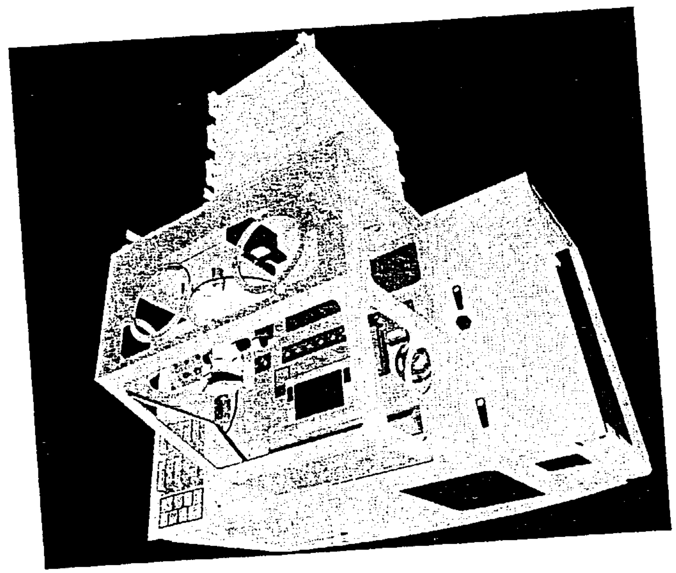


Figure 6