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AN ON-BOARD ISS VIRTUAL REALITY TRAINER

The Virtual Reality Laboratory/ NASA Johnson Space Center

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Evelyn Miralles

Virtual Reality Laboratory
L3 STRATIS – Houston Office
NASA Johnson Space Center
Houston, Texas 77058
281-483-3780
evelyn.miralles@nasa.gov

Abstract: Prior to the retirement of the Space Shuttle, many exterior repairs on the International Space Station (ISS) were carried out by shuttle astronauts, trained on the ground and flown to the Station to perform these specific repairs. With the retirement of the shuttle, this is no longer an available option. As such, the need for ISS crew members to review scenarios while on flight, either for tasks they already trained for on the ground or for contingency operations has become a very critical issue.

NASA astronauts prepare for Extra-Vehicular Activities (EVA) or Spacewalks through numerous training media, such as: self-study, part task training, underwater training in the Neutral Buoyancy Laboratory (NBL), hands-on hardware reviews and training at the Virtual Reality Laboratory (VRLab). In many situations, the time between the last session of a training and an EVA task might be 6 to 8 months. EVA tasks are critical for a mission and as time passes the crew members may lose proficiency on previously trained tasks and their options to refresh or learn a new skill while on flight are limited to reading training materials and watching videos. In addition, there is an increased need for unplanned contingency

repairs to fix problems arising as the Station ages. In order to help the ISS crew members maintain EVA proficiency or train for contingency repairs during their mission, the Johnson Space Center's VRLab designed an immersive ISS Virtual Reality Trainer (VRT).

The VRT incorporates a unique optical system that makes use of the already successful Dynamic On-board Ubiquitous Graphics (DOUG) software to assist crew members with procedure reviews and contingency EVAs while on board the Station.

The need to train and re-train crew members for EVAs and contingency scenarios is crucial and extremely demanding. ISS crew members are now asked to perform EVA tasks for which they have not been trained and potentially have never seen before. The Virtual Reality Trainer (VRT) provides an immersive 3D environment similar to the one experienced at the VRLab crew training facility at the NASA Johnson Space Center. VRT bridges the gap by allowing crew members to experience an interactive, 3D environment to reinforce skills already learned and to explore new work sites and repair procedures outside the Station.

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1. About the VRLab - Ground Based Training

The VRLab is a crew training facility that uses a unique custom developed 3D graphics software product called Dynamic On-board Ubiquitous Graphics (DOUG). The DOUG software package is the meat of the virtual reality system, as it provides a comprehensive representation of the ISS exterior. This software with a suite of real-time simulations provides an immersive virtual reality environment for high fidelity training scenarios for EVA and Robotics tasks. With this VRLab system the crew members can choreograph and rehearse their on-orbit procedures. It is rapidly re-configurable, providing an unlimited number of scenarios that can be evaluated at a fraction of the cost of other more rigid systems. The main training scenarios provided by the VRLab are:

- **SAFER (Simplified Aid for EVA rescue) Training scenarios.** It is a mini-propulsion

unit that provides contingency maneuvering capability for a space-suited crew member during extravehicular activity or EVA operations. The SAFER provides self-rescue capability for an EVA crew member who has become inadvertently separated from the International Space Station (ISS).

- **The Robotic Workstation (RWS).** A mockup that represents the Cupola on-board ISS, which allows integrated training of virtual EVA operations with robotics support. The RWS (*see Fig. 1*) allows crew members to practice flying the Space Station Remote Manipulator System (SSRMS) and is used with and without EVA crew members.

The unique fidelity of the VRLab graphic system allows crew members to practice flying the SSRMS with realistic lighting conditions that is essential for critical operations as the capture of visiting vehicles such as: Dragon, Cygnus or the H2 Transfer Vehicle (HTV) or any future commercial vehicles. To simulate the EVA environment, the VRLab can support operations of the RWS and two EVA crew members simultaneously, also allowing the crew members to practice the communications and teamwork they will use during an actual EVA.

- **Mass Handling scenarios.** The mass handling simulation consists of a robot (or two), with six degrees of freedom that allows crew members to experience handling payloads of various sizes, masses, and center-of-gravity locations, in a simulated and controlled microgravity

environment or zero-g. The two robots allow for two crewmembers working together to practice joint control or transfer of large payloads. (see Fig. 2)

- **EVA Training procedures development.** The crew members can practice translating along the exterior of the Station, just as they would on a real EVA. They can examine different work sites and translation paths to familiarize themselves with where they will go for a planned EVA, or where they might go for a contingency EVA. This is a unique capability since there isn't any other place in the world with the high fidelity up-to-date 3D model of the ISS.

To immerse the EVA crew members in the virtual environment, the VRLab has two Head-Mounted Displays (HMDs). Each HMD has a separate display for each eye, thus providing the 3D virtual environment. Incidentally, the current lab HMDs were somewhat a result of the VRT design system. Because of the development of the VRT, the VRLab staff discovered that improved HMD methods and materials were becoming available at reasonable cost. While the previous generation of HMDs in use at the VRLab was very good, the next generation developed after the VRT using new optics and LCD displays now provides an improved immersive experience, with a resolution of 1280 x 800 per eye and a 110 degree horizontal field of view.

Today, the VRLab is the only training facility where crew members can train for operations on

the entire exterior of the ISS. Given the vast size of the Station, there are no full-size replicas of the complete spacecraft. DOUG is used in the VRLab to provide a 3D, immersive environment for the EVA crew members, and it is also available to crew members, flight controllers and instructors for use on their individual computers. The software has been integral in the development and execution of EVAs and Robotics operations throughout ISS assembly.



Fig. 1. Robotic's Workstation



Fig. 2. Mass-Handling equipment

2. Understanding the training problems on flight and the need for a VRT system.

Even though the current DOUG graphics software is available in the ISS on-flight and used extensively for crew training prior to their flight, an immersive 3D environment on-board the Space Station was needed to provide the crew members with a similar knowledge training experience that they had before their mission. An immersive 3D environment allows them to get familiarized with the work site efficiently and to better understand location, orientation, and operations when positioned outside the Space Station during an EVA.

The learning benefits of 3D immersive environments are a well-studied topic and have identified the positive fast contribution to conceptual understanding. The VRT was also needed to augment current Station on-board trainers, such as the Simplified Aid for EVA Rescue On-board Trainer (SAFER SOT), which continues training done on the ground but is currently very limited due to the reduced field of view and lack of a sense of immersion because it is run on a regular laptop 2D display. Several other virtual reality helmet systems have been flown previously to the ISS, but their use has been limited to a few unique tasks due to their targeted capabilities and the certification and time required preparing individual scenarios for flight. With the use of the VRT all these concerns are taken care off.

2. Initial VRT design goals and approach

- ❖ To provide an immersive visual experience.

- ❖ To use as much of the existing on-orbit equipment and materials as possible.
- ❖ Any additional hardware that must be built and flown has to be as simple as possible to reduce cost and flight certification time.
- ❖ Desired properties of the optical system:
 - Utilize as much of the laptop screen as possible to maximize resolution.
 - Have good stereo overlap.
 - Provide a wide field of view
 - Place most of the laptop mass over center of head to minimize head pan inertia.
 - Have a large enough exit pupil to accommodate variances in inter-pupillary distance without requiring optical adjustment.
 - Accommodate add-on prescription lenses for those who needed correction.

One of the key considerations that drove the design of the VRT unit was to minimize the time and cost of flight certification by utilizing many components already on-board the ISS. These include: laptops to run the HD 3D visual graphic engine; a hand control module (HCM) to provide the inputs for flying and menu navigation; and a web cam, to provide the tracking feedback needed for immersive head movement within the virtual environment. There was also the need to modify a version of the DOUG graphic software to support the new VRT mode, and it also had to be easily up linkable to the ISS laptop computers. New hardware components that needed to be created for the VRT included: optical system with lens adapter capability, and a viewing hood that

would fit over the screen of the on-board laptops.

3. Bringing VRT On-board the ISS

In today's spaceflight environment, the main ISS assembly is complete, and the purpose of EVAs has shifted from ISS assembly to smaller, less frequent maintenance and repair tasks. As such, the crews that perform these EVAs might not have the luxury of training the tasks on the ground prior to their flight. Virtual reality provides the clear advantage of "seeing" and training tasks before they must be performed.

In a critical contingency EVA scenario, where hardware must be repaired or replaced in a short time frame, the desire to have a Virtual Reality Laboratory on-board the ISS became clear. But how do you replicate a complicated facility, which uses electromagnetic-based motion tracking, extensive computational resources, and several operators to keep everything running? Trade studies were done to survey current commercial virtual reality systems, but even with recent advances in technology, none of the systems provided the desired capability; most notably, a wide enough field of view and high resolution.

The VRT (*see Fig. 3*) inspiration came in an unexpected form, as a laptop screen on the head. A prototype was designed and built, looking deceptively simple. The VRT consists of a hood that attaches to a laptop screen, with an integrated optics assembly. The user simply straps the laptop to their head - a method only suited for the micro-gravity environment on the ISS. The modified DOUG software provides the visuals, with a mode to split the laptop

screen's horizontal view with a normal resolution of 1920 x 1200 into two views, left and right eye images. The optics assembly provides the lenses required to allow the user to focus on and converge the two images, thus providing a 3D environment with a resolution of 960 x 1200 per eye and an almost 100 degree horizontal field of view.

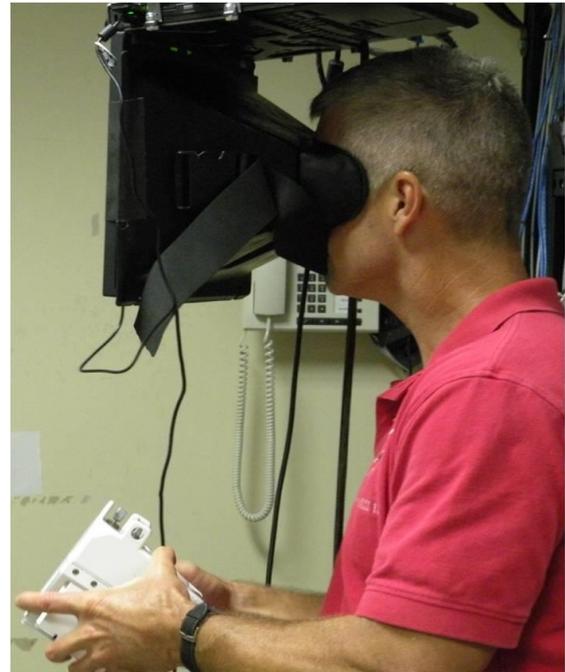


Fig. 3. VRT Prototype in use.

With the visual scene taken care of, the next issue became control. As mentioned above, the VRLab uses a professional motion tracking system, as well as custom gloves to track the location of the crew members' heads and hands to provide feedback in the virtual environment. Launching such a system to the ISS was simply not an option due to cost, spatial constraints, etc. Again turning to the equipment already available on-board, the engineers at the VRLab decided to use a web cam attached to the back of the laptop screen to provide head tracking.

Software embedded within the DOUG package then tracks the optical flow of the scene via the web cam to adjust the visuals as the crew members moves their head. Another item already on-board, the Simplified Aid for EVA Rescue (SAFER) hand controller, was chosen to maneuver through the visual scene. The SAFER is the “jet pack” used by EVA crew members for emergency rescue if they were to float off of structure untethered.

4. The VRT components

Building new components

- **The Optics:**

The optics was designed with two lenses, one is a Plano-convex 43mm diameter with 77 mm FL and the other is a Plano-concave 50mm diameter with -200 mm FL (see *Fig. 4*).

By combining one Plano-concave element (50mm dia, -200mm fl) with its planar surface parallel to and facing the screen with a Plano-convex element (43mm dia, 77mm fl) with its planar surface facing the user's eye and angled to the screen by 20 degrees we were able to achieve a stereo overlap of over 44 degrees and create the focal point area for the eye’s pupils to see through and converge the image coming from the laptop screen for an image exceeding 90 degrees of horizontal field of view.

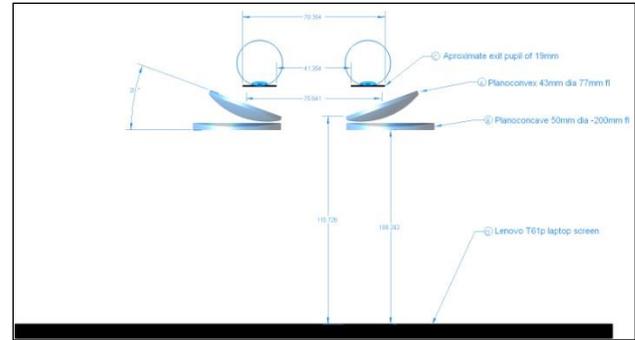


Fig. 4. Optics Design

This particular lens arrangement enables the needed large stereo overlap due to the angular compression that occurs optically as the eye peers towards the bridge of the nose and gives a combined focal length of 125mm and allowing the majority of the laptop mass to sit directly above the head minimizing the head's rotational inertia in the pan left and right directions.

The large lenses also allow sufficient eye relief to permit the addition of prescription lenses for people who needed it and still maintain a horizontal field of view exceeding 90 degrees and a vertical field of view exceeding 75 degrees (see *Fig. 5*)

This particular configuration provides a 19 mm area of focus "sweet spot" to comfortably accommodate several inner pupillary sizes without needing any mechanical adjustment. In order to create this effect, the laptop screen should be placed at a distance of approximately 108 mm (approx. 4.25 inches) away from the Plano Concave lens.



Fig. 5. Optics Design

- **Optics adapters for SuperFocus™ lenses:**

The adapters are an additional metal component created to accommodate the SuperFocus™ prescription lenses used by some of the crew members on-board the ISS as needed (*see Fig. 6*)



Fig. 6. Adapter for corrective lenses

- **The Hood:**

The hood is a pyramid shaped base that encloses the optics and provides the structure that supports the optics assembly at an optimal distance and orientation to the laptop screen. The hood was constructed using a 3D extrusion printer using a special spaceflight rated, flame retardant plastic (*see Fig. 7*)



Fig. 7. VRT Plastic Hood

- **Straps:**

Adjustable straps were added to the final unit to securely hold all parts together during flight to the ISS and to provide support when attaching the hood to the laptop (*see Fig. 8*)



Fig. 8. Retaining Straps

- **The Mask:**

The VRT used an off-the-shelf safety goggle-style mask. A special lip fitting that is built into the hood allows the mask to snap into place on the hood to provide a comfortable fit for the crew member and limit outside light intrusion into the VRT system (*see Fig. 9*)



Fig. 9. Comfort Mask

Using existing components

- **EMU SAFER HCM with Quick Flex PCMCIA card:**

The Extra Mobility Unit (EMU) SAFER Hand Controller Module (*see Fig. 10*) is the unit that allows the crew member to fly the SAFER unit as commanded. It houses both a joystick for directional commands and a liquid crystal display for monitoring the system status from the avionics. The joystick is a four axis controller, used either for translation or rotation depending on the position of a separate mode switch resulting in a six degrees of freedom maneuvering: +/-X (Roll about X), right/left as +/-Y (Pitch about Y) and up/down as +/-Z (Yaw about Z) mapped via a body-centric coordinate frame. An additional button called Automatic Attitude Hold (AAH) is available and can hold any rotation attitude while maintaining translational authority. The Quick Flex card included with the HCM is a technology that provides a dynamic re-configurable interface to adapt the hand controller's I2C command interface to the Station's laptops. It uses a custom

programmed FPGA (Field Programmable Gate Array) chip that provides software performance at hardware speeds. As all the electronic components on-board the ISS are, this technology was also radiation tested before deployment.

The HCM provides the interface necessary to manipulate the menu entries for the VRT since access to the laptop is not possible when the VRT is installed. Additionally the HCM can also be used to navigate through the 3D scene.

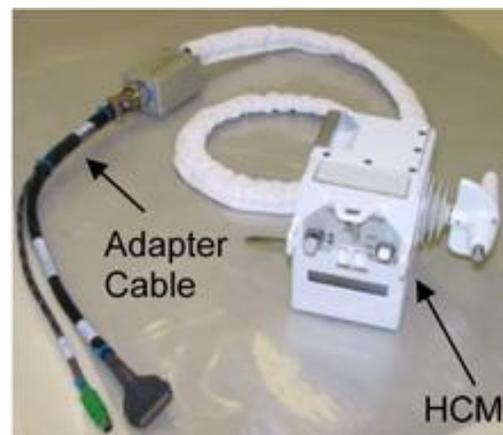


Fig. 10. SAFER Hand Control Module

- **Station Laptop**

The current laptop used on-board the Space Station is a Lenovo ThinkPad™ Series T61p Notebook with the following components:

- Processor Intel Core 2 Duo 2.4GHz
- NVidia Quadro FZ 570M (256MB)
- Basic Memory: 2GB DDR2
- Display: 15.4" 1920x1200
- HDrive 160GB

The laptop runs the DOUG 3D graphic package, as well as numerous other applications commonly used on-board the ISS (see *Fig. 11*)



Fig. 11. Lenovo ThinkPad™ Series T61p

- **Web Cam:**

The web cam used on-board the Space Station is a Logitech™ QuickCam™ Pro for Notebooks with a 960 x 720 HD video format, a 2Meg sensor, Carl Zeiss optics for high quality, RightLight 2 technology (enhance back light), and a clip holder. It records videos at 30 frames per sec and works under Windows using a USB interface. The web cam provides a real-time head tracking capability for the VRT system. When connected and interfacing with the DOUG software, it detects the physical changes in the scene from frame to frame and uses these changes to compute pan and tilt movements of the camera (and thereby the VRT) using a technique called optical-flow. The optical-flow implementation into DOUG was done with the assistance of the OpenCV library available under Windows environments OS (see *Fig. 12*)



Fig. 12. ISS Used Webcam

- **Necessary DOUG Software modification:**

The optical characteristics of the lenses, as well as the canted installation of the optic results in a degree of optical distortion. The 3D graphics of the DOUG software was modified to correct the optical distortion that occurs especially near the center line between the eyes. An inverse distortion mapping was applied to the rendered images before being displayed to the screen resulting in a non-distorted seamless stereo 3D experience when viewed through the optical system.

The Optical Distortion Correction was written as a plug-in for the DOUG software so that future changes to the VRT hardware including the optical assembly and any new laptop can be accommodated without the need to alter the software executable base engine. The DOUG plug-in reads an input with the textual description of the optical assembly and laptop screen from a configuration file. The technique used by the plugin to correct for optical distortion involves the rendering of the scene using a planer projection having a slightly larger FOV than needed to an off-screen buffer followed by the rendering of a distorted mesh textured with the previously rendered scene.

The coordinates for the distorted mesh are determined at run time by ray tracing using a mathematical description of the optical assembly from the eye's location in the direction of each coordinate “in a uniform mesh” to the location where the ray trace intersects the laptop screen. As consequence, the final design of the unit provided for a much better immersive experience than previously used HMD’s for ground training at the VRLab.

5. Final Assembly

The final VRT assembly in zero-g requires attaching the goggle mask to the VRT hood first, then attaching the optics insert to the hood, adding the insert divide to the inside of the hood to physically separate the screen images, and strapping the hood to the laptop screen display (see **Fig. 13**). Then the crew member attaches the USB Web cam to the back of the laptop for tracking and connects the HCM to the Quick Flex card on the laptop. At this point the full VRT system is functional.



Fig. 13. The VRT Assembly

There is an extra frame assembly that can be inserted onto the optics block, for use with the crew member’s SuperFocus™ prescription

lenses, if they need corrective optics. This assembly is separate and only use if needed (see **Fig. 14**)



Fig. 14. A View through The VRT Lenses

6. On-Board Training with the VRT

The initial use of the VRT includes EVA procedure review and EVA contingency operations familiarization, in addition to SAFER proficiency training. The crew members have a menu option from the VRT (see **Fig. 15**) to select the task to perform such as, playing a pre-configured EVA movie generated by trainers on the ground prior to an EVA activity or a SAFER recue run or simply fly around Station for spatial awareness.



Fig. 15. The VRT Menu

Astronauts have been using the DOUG software package on-board the Station and Shuttle for EVA and Robotics support throughout assembly of the ISS. The VRT system (*see Fig. 16 & 17*) takes the capability to the next level by providing an immersive 3-D environment on flight. Some ideas for future training using the VRT include: integrated EVA Robotics training through networked laptops on-board, some potential augmented reality applications and for automated threshold eye perimeter exams to measure eye changes that will help in quantitating the induced hypertension vision alteration problems encountered by crew members in and post flight.

By making use of existing ISS hardware (laptop, web cam, hand controller, DOUG software, etc), the certification process to fly the hardware was simplified and expedited. The VRT hardware was manifested and launched on ATV4 June 5, 2013, and will likely be put to use quickly by the ISS crew prior to a set of planned summer EVAs.

7. Conclusion

The VRT system delivers an efficient way to help crew members maintain proficiency and review procedures for a previously trained EVA task. But most importantly the VRT allows crew members to prepare and train for contingency EVA scenarios when they occur. The smart design of the VRT uses basic components and incorporates parts already available on the ISS, creating a very useful, versatile, and unique 3D training capability on-board the ISS as it is the first fully immersive virtual reality system available on-board the Space Station.



Fig. 16. Astronaut Testing The VRT



Fig. 17. The VRT

8. Biography

Evelyn Miralles

Received a B.A. in Computer Graphics, a B.S. in Computer Science and an MBA in Management of Technologies from the University of Houston at Clear Lake, Texas. She has worked at NASA for over 20 years and currently serves as a Principal Engineer and Lead VR Innovator at the Johnson Space Center Virtual Reality Laboratory, a crew training facility used insensibly during the Space Shuttle

and the International Space Station programs. She was a primary developer of the DOUG software package used extensively for astronaut training, both on the ground and on-board the Station. With numerous contributions to NASA's crewed spaceflight activities she has most recently played a significant role in the development of the Virtual Reality Trainer, a highly immersive 3-D environment for use on-board. She recently received last Dec 2012 a well recognize Space Flight Safety award from the NASA astronaut office.