Training Astronauts using Hardware-in-the-Loop Simulations and Virtual Reality

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The commercial market has recently started giving significant attention to virtual and augmented reality, even though the technology has been around for many years. The Virtual Reality Training Lab (VRL) at the NASA Johnson Space Center has been using virtual reality to train astronauts for decades. This paper will focus on describing three major Hardware-in-the-Loop VR simulation systems, the Simplified Aid for EVA Rescue (SAFER) system known as the "jetpack", the Mass Handling System nicknamed Charlotte, and a simulated robotics environment for collaborative mission evaluation. Two of these systems are critical for astronaut training. Crew must certify on SAFER and go through the Charlotte Mass Handling training prior to flying to the International Space Station (ISS). Typically, they also complete at least one collaborative visualization session to review any planned Extra Vehicular Activities (EVAs), or spacewalks, before an assigned flight. Given the volatility of new technologies, the graphics and simulation environments used are maintained to be hardware agnostic to preserve a high level of fidelity. Utilizing VR for astronaut training has proved to be effective and essential for these specific systems.

I. Introduction

Throughout the years, astronauts have and will continue to train in various facilities and environments to prepare for space. During the Space Shuttle missions, astronaut training was task specific, which encouraged the exploration of virtual reality as a training solution. As time progressed, the increasing complexity of these tasks, the need to visualize the full space environment and structures, and emerging technologies all propelled the use of virtual reality for astronaut training. The Virtual Reality Training Laboratory (VRL) was adopted early on as a training facility capable of modeling entire space vehicles in their true configuration and in an immersive environment. The VRL also integrates real-time, hardware-in-the-loop simulation systems and provides training capabilities that enhance what astronauts learn in other facilities. Given the unforgiving and high-risk nature of space, astronauts need to be prepared for any number of situations. The Neutral Buoyancy Lab (NBL), Space Vehicle Mockup Facility (SVMF), NASA Extreme Environment Mission Operations (NEEMO), and VRL are just a handful of necessary training facilities that are all used in parallel to provide a complete training solution for space exploration. The VRL is frequently used to train for EVA systems such as SAFER, Mass Handling, and integrated robotics and collaborative sessions to refine and rehearse for upcoming spacewalks.

II. Background and History

Soon after the Hubble Space Telescope was deployed in 1990, an issue with the primary mirror was discovered. [1] A small team at NASA Johnson Space Center began exploring the use of VR for high-dexterity tasks to aid in the

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Hubble repair training. This was dismissed quickly since the Weightless Environment Training Facility (WETF), the predecessor to the NBL was already providing this type of training with the physical tools, mockups, and space suits. Using VR for this type of training was deemed redundant, especially since the VR hardware then was not suited for high fidelity graphics or tracking. On the other hand, the WETF had physical limitations due to replicating large structures. At the time, the full configuration of the Hubble Space Telescope did not fit in the WETF. Thus, the mockup was physically divided into parts for training, lowering environment fidelity and introducing a window of opportunity for the VR team. This team over the years has been a handful of engineers who specialize in a mixture of software, 3D graphics, VR, simulations, aerospace, robotics and hardware. Some members of the original team continue to work at the VRL.

The team has developed and maintained a custom-made 3D graphics software package for some time, which evolved into what is now called Dynamic On-board Ubiquitous Graphics (DOUG). They utilized this software to construct an integrated graphical representation of the Hubble Space Telescope, the orbiter, and the shuttle robotic arm. VR was integrated to the graphics software and used to immerse a crew member at the end of the shuttle arm and visualize the Hubble repair worksite. This use case of VR was determined to be invaluable since no other training environment provided a visually immersive perspective of the full vehicle-arm-telescope worksite. Soon after this, in 1992, the Integrated EVA RMS Virtual Reality Training Facility was formalized, now commonly known as the VR Lab. [2]

Fig. 1 Virtual Research headset and fiber optic gloves worn in one of the first VR astronaut training sessions. (NASA, 2019)

The new lab's focus was to develop, maintain and support astronaut training for the Hubble Telescope repair missions. This included developing exterior3D models, maintaining the graphics software, integrating graphics into the simulation software for the shuttle robotic arm (Remote Manipulator System - RMS), and providing training support for these integrated virtual sessions. Not only was the team supporting operations and training, they were simultaneously developing and maintaining the systems while getting feedback from the instructors and astronauts in

the process. Instant feedback was key to the success of VR for training, allowing the creation of solutions to problems other training environments could not resolve efficiently. [2]With VR already being used for training, the VR Lab took on another simulation system in 1994. The Simplified Aid for EVA Rescue (SAFER) flight training system was

Fig. 2 First N-Vision Datavisor HMD and Cyber Gloves used for astronaut training. (NASA, 2019)

already part of the astronaut training flow but was being taught on a big screen television with 3D glasses for depth perception. The VR Lab integrated the simulation with a VR Head Mounted Display (HMD) to significantly improve spatial cognition.

Four years after first exploring VR for training, the VR Lab had already used two different VR HMDs and were on their third, nicknamed "googly eyes", an N-Vision Datavisor VR Headset with CRT displays and 1280x1024 resolution in each eye. This HMD drifted over time, causing distortion. It needed to be carefully calibrated by hand once every couple of months by Brad Bell[5], strategically scheduled at the end of the day to avoid induced cyber sickness throughout the workday. The head, torso and hands were being tracked by the MotionSTAR Flock of Birds electromagnetic tracking system, which required a controller for each sensor at the time. Additionally, hand gesture tracking was done using the Cyber Glove, which was found to be the most viable hand gesture tracking technology in the early 1990s. [2]A few years after SAFER was integrated with VR, one more training system was introduced to the Lab. The McDonnell Douglas Charlotte IVA robot was modified and adapted for micro-gravity mass handling training. Charlotte had been used and designed initially to monitor experiments onboard the SpaceHab launched in 1995. With significant modifications, it was used to simulate handling masses of greater than 500 pounds in micro-gravity and integrated with virtual objects in an immersed VR environment. [3] In 1997, after feedback, testing, and validation from crew and engineers, the Charlotte Mass Handling Robot was officially introduced to the astronaut training flow. Prior to Charlotte, astronauts used the Precision Air Bearing Floor to familiarize themselves with handling masses in micro-gravity. This method required full mockups with accurate mass properties and was very limited in degrees of freedom. Charlotte allowed for effortless graphical reconfiguration of masses and physical interfaces. [2]

[5] Bradley Bell, VR Lab Principal Engineer, Founding Member and original DOUG Author

Fig. 3 Charlotte Mass Handling Robot being used for astronaut training with N-Vision Datavisor HMD. (NASA, 2019)

The VR Lab continued to support astronaut training for all Shuttle missions and during International Space Station (ISS) assembly. Throughout the years, the VR team continually developed high fidelity exterior graphical models of the ISS, including cable routings, handrails, and decals. This graphics software known as DOUG was deployed throughout all of NASA Johnson Space Center and used in multiple integrated simulation facilities such as the Systems Engineering Simulator (SES) and the Space Station Training Facility (SSTF). The team developed a graphical user interface for DOUG and soon after deployed it for use for EVA and Robotics planning, review and situational awareness. It has and will continue to help prepare astronauts for tasks required during their mission, as well as during training. DOUG is also used to generate EVA procedure animations that includes both EVA crew procedures and SSRMS positions for crew review and training. In 2001, DOUG was deployed for astronaut use on-board the ISS and used to continue training once they were in space. [2]

As VR technology progressed, the VR lab continued to adopt commercially available hardware. At the time, HMDs and tracking systems were hundreds of thousands of dollars and a very small market. In 2004, the VR Lab began creating custom gesture tracking gloves with strain gauges in every finger. One of the biggest limitations in VR immersion hardware to this day is hand gesture tracking, since most finger-articulated gloves used for training experienced wear and tear, leading to significant time and effort being spent to repair them or create backups. At this time, the lab had moved on to the Motionstar Ascension electromagnetic tracking system which eliminated individual controllers for each sensor. In 2005, N-Vision released the Datavisor 80 HMD, which still had CRT displays. [2]

Fig. 4 N-Vision Datavisor 80 HMD used for astronaut training with custom made hand gesture tracking gloves. (NASA, 2019)

The VR Lab transitioned to this HMD and three years later, in 2008, started making custom modifications using cell phone technology. They modified the displays to micro-OLEDs providing 800×600 resolution in each eye and eliminated the need to calibrate the HMD. Two years later, in 2010, the Engineering DOUG Graphics for Exploration (EDGE) launched refurbishing DOUG and providing more integration support with other simulation systems around NASA. In 2012, with the release of the first Oculus Development Kit (DK1), the VR Team decided to custom make their own HMDs using the LCDs from the DK1s and custom-made hardware, increasing the resolution of the HMDs to 1280×720 in each eye. [2]

Also in 2012, it was requested that an immersive solution for SAFER training on-board the ISS be developed. With DOUG already on-board the ISS, astronauts were able to practice flying SAFER, but only on the 2D laptop screen with a system called the SAFER On-Board Trainer (SOT). A year later, the VR team successfully deployed the first virtual reality headset used in space, the Virtual Reality Trainer (VRT), unofficially known as the laptop-on-the-head. [2]

Fig. 5 Left: Shows the original Laptop-on-the-head SAFER training system used by Astronaut Shane Kimbrough and first use of VR in space. Right: Shows current VRT SAFER training system with modified Oculus HMD used by Astronaut Christina Koch. Both on-board the ISS. (NASA, 2019)

Back on Earth, the VR Team continued to make their own custom headsets. In 2015 they leveraged from the OLEDs in the Oculus DK2 which provided a wider field of view and 1920×1080 resolution in each eye. As technology progressed, VR became more comfortable, reliable, and affordable, and the graphical fidelity of the ISS model improved. This allowed the VR Team to focus on some significant upgrades to their VR training systems and move on from building their own VR headset solutions. [2]

In 2017, the first two major upgrades stimulated from commercially available and affordable HMDs took place. With some hardware and software modifications to adapt VR for micro-gravity, and the limited graphical performance of laptops on the ISS, the VR team launched an Oculus headset to replace the Laptop-on-the-head system. At the VR Lab, the HTC Vive HMDs and Lighthouse tracking system replaced the custom-made HMDs and MotionSTAR tracking system. In 2018, the hand gesture tracking was overhauled using a magnet and the Vive tracking pucks to track open and closed hand positions. Shortly after, the lab upgraded to HTC Vive Pro HMDs and tracking system. [2]

Today, the lab is completely wireless and uses the Vive Pro HMDs with the wireless adapter and three tracking pucks for hands and torso tracking, as well as hand gesture recognition. One additional puck is utilized to track the SAFER Hand Controller during SAFER training. The lab continues to develop, maintain and provide support for DOUG on-ground and on-board. The VR Lab also continues to provide real-time hardware-in-the-loop astronaut training for SAFER, Mass Handing and integrated robotic/EVA systems.

Fig. 6 Current Vive Pro HMD used for astronaut training being used by Astronaut Jessica Meir. (NASA, 2019)

III. Current VR Hardware and Software Setup for Astronaut Training

The VR Lab uses the HTC Vive Pros and Lighthouse Tracking system for training. Two immersive stations are used, referred to as EV1 (Extra Vehicular) and EV2. These stations allow having two crew members immersed in the same virtual environment at the same time, simulating how astronauts perform EVAs always in pairs referred to as EV1 and EV2. The stations are configured back to back in the same tracking space to allow for efficient interaction when handling the Charlotte robot. Each station has a Vive Pro HMD, a Wireless Adapter, two custom-made gloves with one Vive tracking puck on each and a torso tracking puck attached to the back of a back-posture brace. Also, each station has an ergonomic chair which restricts movement within the tracking space and encourages only arm and hand movement.

Fig. 7 Current VRL Training Setup. EV1 station used by Astronaut Anne McClain on the right of the image and EV2 station used by Astronaut Nick Hague on the left. Not pictured: upgraded torso tracker attached to back posture brace and wireless adapter on HMD. (NASA, 2019)

The VR Lab remains hardware agnostic and the current software can be deployed on any commercially available HMD and tracking system. SteamVR and the Vive Pros are the current preferred solution for training, since the tracking systems can easily be adapted to track multiple elements by simply adding additional tracking pucks, and multiple HMDs can be tracked with the same lighthouses in the same tracking space. The ability to be wireless is also a benefit of this system, especially when instructors and other crew are around the tracking space watching the training sessions.

The EV1 and EV2 HMDs are deployed on two different Windows PCs each running a Nvidia 1080Ti Graphics Card. A DOUG client is launched from a Linux server process that communicates specific scene nodes to be displayed in each HMD graphical environment. All other visuals used to support training run DOUG in the same environment and are deployed in Linux machines. Depending on which training simulation is executed, different DOUG node structures and scenes are used. These are custom made and modified to provide different plugins for different training systems.

IV. Simplified Aid For EVA Rescue (SAFER) Training System

The SAFER system has been part of astronaut training since before 1994, when SAFER was first deployed during STS-64 in an untethered test by astronaut Mark Lee. [4] SAFER is a “jetpack” backpack attached to the Portable Life Support System (PLSS) on the back of the Extra Vehicular Mobility Unit (EMU). SAFER was designed to be used as a redundant system in the event an astronaut becomes untethered from the ISS while performing a spacewalk. During the shuttle missions, if a crew member became untethered, the shuttle was responsive and maneuverable enough to fly and rescue that crewmember. As the shuttle program ended and the ISS program developed, it was recognized the ISS would not be capable of moving in such way that it could perform a rescue in the event a crew member became detached during a spacewalk. Although the first and last time SAFER was flown untethered in space was in 1994, the SAFER system is still required to be used during every EVA.

In order to train astronauts to use SAFER, the VR Lab maintains and deploys a hardware-in-the-loop real-time simulation using Trick, a NASA custom simulation development framework. The SAFER Trick simulation provides and controls all the physics, dynamics, sensor data, avionics, power, and thruster logic models. The Trick simulation communicates with the DOUG software and updates pre-defined nodes real-time in the graphical environment. This system uses a physical flight-like SAFER Hand Controller Module (HCM) and avionics system. The HCM is physically connected to the avionics hardware, which is then connected to the simulation machine that reads and processes the data through the Trick simulation.

Instructors use this simulation in two different ways when training astronauts. The first portion, the introduction

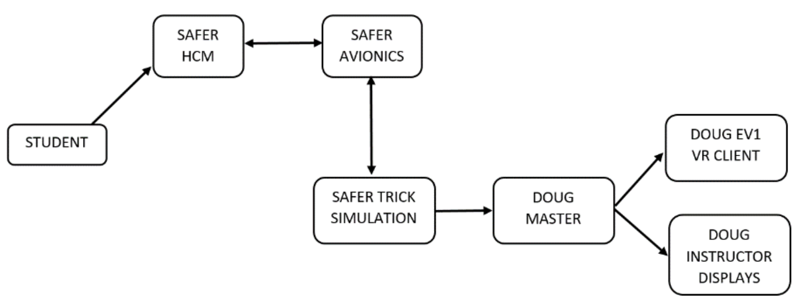

Fig. 8 Diagram showing VRL SAFER simulation system interfaces.

class to SAFER, focuses on the hardware and the functionality of SAFER. The simulation is used during this part of the class to simulate a SAFER checkout which would be done IVA, inside the ISS before a spacewalk. A checkout of the system looks for system failures in all the subsystems of SAFER such as the thrusters and rate sensors. Astronauts use the HCM to perform a checkout, manually inputting commands into the HCM as directed by the HCM LED screen. The instructor can use a simulation interface to insert system failures such as a failed thruster. This will trigger an error message on the HCM LCD and is used to train how to react to certain system failures.

The second part of the SAFER training session includes flying the SAFER system in VR. During this part of the training, the real HCM is used and offloaded through a pulley system to reflect weightlessness in space. A Vive puck is mounted in front of the HCM to track and visualize the HCM in the virtual environment. The EV1 VR station is used for SAFER training, utilizing the gloves, torso and wireless headset. A modified DOUG environment is deployed that has SAFER specific nodes including the virtual HCM node, and the ability to display different trajectory lines and simulation data for the instructors monitoring the SAFER flight runs.

Fig. 9 Astronaut Nicole Mann using the SAFER VR Training simulation. Not pictured: upgraded torso tracker attached to back posture brace and wireless adapter on HMD. (NASA, 2019)

During the VR portion of the SAFER training session, astronauts are put in rescue scenarios where they are thrown off an exterior location on the ISS and tumble away from structure for 30 seconds. These 30 seconds are to simulate becoming detached from structure, jettisoning any large tools or equipment greater than 60lbs, and the time it takes to deploy the HCM from the SAFER unit. After this delay, the HCM can be powered on and flight training begins. The student must fly successfully back to structure at a reasonable velocity to be considered rescued. In VR they have the capability of grabbing onto handrails as they approach structure.

A VR Team member controls the simulation configuration for VR training. The instructor can request different body locations and orientations outside of the ISS such as the Airlock, S0 Truss, Node 2, etc. The separation direction, speed and rotation rates, lighting, and fuel quantity are also customizable. For certification scenarios, astronauts must be proficient at flying back to the ISS after being thrown off at a one foot per second separation rate and 30 degrees per second rotation rate in every axis from the outside of the airlock heading nadir toward Earth. During a typical training flow, astronauts practice flying SAFER in many configurations multiple times before being required to pass a certification flight.

Once certified on ground in the VR Lab, it could be months before astronauts launch to the ISS and even longer before they perform a spacewalk. They use the SAFER VRT to refresh SAFER flights training onboard the ISS. Currently this system uses a flight-like HCM, a modified Oculus, and DOUG on the flight laptop running a modified version of the Trick SAFER simulation. The on-orbit simulation bypasses the avionics system and uses direct HCM inputs. Astronauts themselves can customize their cases and configure their separation locations and speeds to practice different flights scenarios. SAFER VRT is currently the first and only VR astronaut training system onboard the ISS.

V. Mass Handling Training System

The Charlotte Mass Handling Robot uses eight motors, connected via cable to each of the external vertices of the robot interface cube. On the front face of the cube, six JR3 multi-axis force-torque sensors are attached in-between the payload interface plate and the robot interface cube. The payload interface plate can be reconfigured by changing the handrail interfaces and recalibrating the Charlotte robot and graphics to match whatever payload scenario instructors want astronauts to train on. The sensors read the input forces and torques applied to the interface plate and communicate to the Charlotte Trick simulation. The simulation drives the motors and the robot to move according to the configured payload mass properties. The simulation also updates the DOUG visuals on the HMDs in each EV station as well as the graphics in all the other instructors' views.

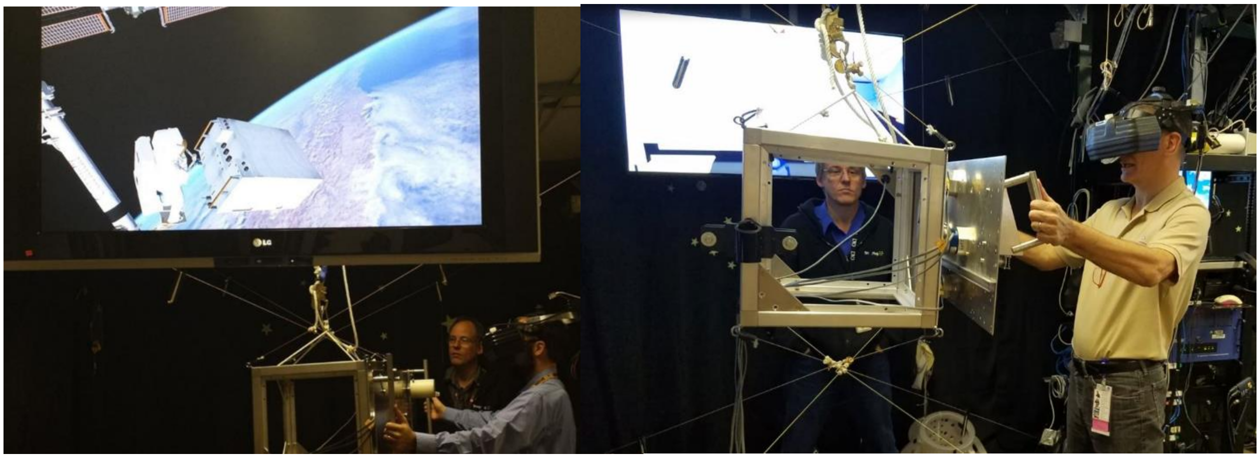

Fig. 10 Charlotte Mass Handling Robot used for training. On the left DOUG visuals showing EV2 handling a payload, on the right Charlotte being used for training. (NASA, 2019)

The VR Lab has two Charlotte robots, one for each EV station. Both robots can be deployed simultaneously in the same VR environment, configured to a single virtual payload. Thus, two crew members can simulate manipulating one payload in VR with two physically different and independent Charlotte robots. This mass handling simulation provides the closest simulated micro-gravity mass handling sensation to what astronauts experience in space. Additionally, it is easily reconfigurable and does not require physical payloads that have to mimic real mass properties. Astronauts typically complete one Mass Handling Training session before they leave to the ISS. Each training session is completed with two or three different payloads, all with masses greater than 500 pounds. Each crew member must practice manipulating the virtual payload and installing it to specific and unique structural interfaces. These interfaces are also simulated as a contact model in the Charlotte Trick simulation. Once the virtual payload becomes in contact with the virtual interface, the simulated contact model communicates with the robot to respond accordingly. This provides a real sensation of handling and mating these payloads to their unique interfaces. Crewmembers train using with Charlotte until they feel comfortable handling large payloads in simulated micro-gravity.

VI. Integrated Robotics and EVA Worksite Training System

Since the start of the VR Lab, integrated robotics and EVA training has been critical to helping familiarize astronauts with expected spacewalk worksites and enhancing the collaborative development of EVA and robotics procedures and training. During this type of training, all EV stations are used as well as the simulated Robotic Workstation (RWS). On-board the ISS, during EVAs, one crew member inside the ISS operates the Space Station Remote Manipulator System (SSRMS), also known as the Station Robotic Arm or Canadarm2. Depending on the EVA, there could also be an astronaut attached to the end of the arm via Articulating Portable Foot Restraint (APFR). This astronaut is manually moved by the astronaut inside the ISS around to different worksites on the outside of the ISS. A third astronaut could be near a worksite handing off payloads or receiving payloads from the astronaut on the robotic arm. This type of EVA is complex and requires a collaborative effort not only from the astronauts performing the spacewalk, but from many different training and procedure development groups on the ground.

Fig. 11 Astronaut Jessica Meir using the VR Lab's RWS system to move EV1 on the simulated SSRMS for the Alpha Magnetic Spectrometer (AMS) Repair training. (NASA, 2019)

The VR Lab is integral to practicing collaborative worksite visualization, robotic arm manipulation, crew member communication, and EVA and Robotic procedure development, all simultaneously in a shared environment. In the VR Lab, one astronaut can sit and manipulate RWS with real hardware using an SSRMS Trick Simulation which drives the graphical robotic arm in all DOUG views, including EV1 and EV2. During these training sessions it is also important astronauts practice communicating in a specific reference frame. The crew member inside the ISS could be in one orientation and the one being manipulated at the end of the arm could be in a completely different orientation, therefore "up" or "down" can have very ambiguous meanings. Astronauts can use their hands-on experience, and work with instructors and systems specialist to develop and refine spacewalk procedures during these training sessions, as well as note areas of concern, or further study in another training environment such as the NBL. At the VR Lab, crew and operation planners can visualize full, integrated structures in their true configuration as they would appear in reality. Since the DOUG graphics are easily reconfigurable, and can be updated to reflect what will be installed on station in the future, an accurate, up to date configuration can always be represented for training sessions.

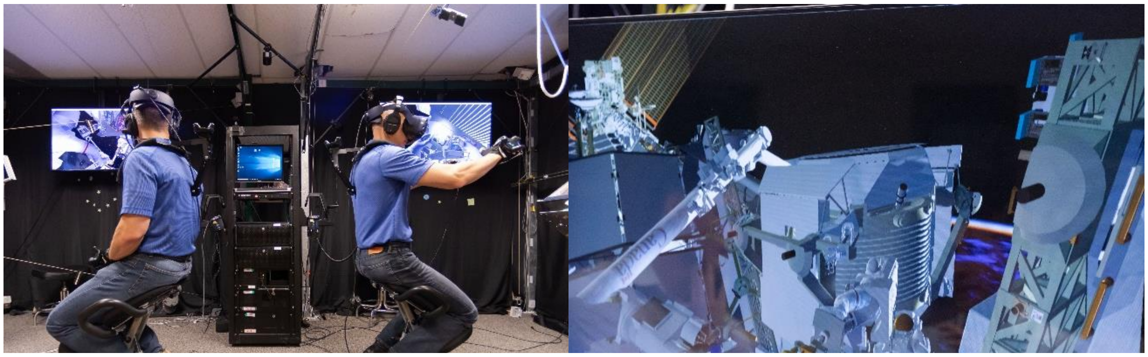

Fig. 12 Astronaut Luca Parmitano pictured as EV1 on the left image and at the end of the robotic arm on the right image along with Astronaut Andrew Morgan as EV2 pictured near EV1 during an integrated Robotics and EVA training session for the AMS Repair EVA. (NASA, 2019)

Typically, this training session occurs months before the respective crew leaves for the ISS. Since EVAs are planned far in advance, training is scheduled around a specific group of astronauts that will be performing specific tasks during their scheduled time aboard the ISS.

VII. Conclusions and Future Work

The VR Lab has used VR integrated with hardware-in-the-loop simulation systems to train astronauts for decades. These unique systems were developed and continue to be used for training because they are the only viable solution to very difficult training problems. The VR Lab does not attempt provide a one solution for all system, instead it has worked closely with astronauts and instructors to help overcome the limitations other training environments and facilities inherit.

As we prepare to support landing back on the moon, and looking toward deep space exploration missions, the VRL has leveraged from the Prototype Immersive Technologies Lab (PIT). At the PIT, the VR Team can explore and develop with new hardware and software systems before deploying them in the VRL. The VRL is continuously used for astronaut training and cannot be used to test out technology. The PIT Lab will be essential in our future missions to develop, innovate and test technologies before we apply them for astronaut training. The VRL continues to support astronaut training for the ISS and will continue to advance and adapt to new technologies along with the PIT Lab as we prepare to train astronauts to return to the moon.

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