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Using the method of Loci in virtual reality to reduce robotic operations training time of astronauts

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Abstract

The European Astronaut Centre (EAC), in Germany, trains and supports astronauts for space missions on board the International Space Station (ISS). As part of their preparations, future ISS crew members must train to operate the Mobile Servicing System (MSS) safely. The MSS is the collection of robotic systems that includes the Space Station Remote Manipulator System (SSRMS–also known as Canadarm2), a 17m-long robotic arm that can be piloted from inside ISS.

Astronauts may need to complete various operations with the SSRMS, such as capturing free-flying visiting vehicles, or moving other astronauts between worksites during Extravehicular Activities (EVAs, also known as spacewalks). However, operating SSRMS requires precise technique, since there are only limited means for the operator to monitor the arm's surroundings, and mistakes can cause crew injuries or severe hardware damage. Moreover, predicting the arm's motion can be challenging, since the arm maneuvers via seven revolving joints, while the operator commands using only two hand controllers.

Instructors prepare astronauts to execute complex tasks through lengthy training with replicas of the arm commanding interface and an interactive 3D simulation of its movements. With that training system, achieving the first level of proficiency takes between 20 and 30 hours of training. The same system is also used to train some ground personnel, so they may support the crew in orbit. Unfortunately, such volumes of students elevate the required teaching time to levels that challenge the instructor's team capacity. To lower the training time, the eXtended Reality Laboratory of EAC and the National Aeronautics and Space Administration CX-2 Robotics operation team launched a Joint Investigation into Virtual reality for Education (JIVE).

JIVE changes the training paradigm, from being purely simulation-based to presenting knowledge in a purposely-built museum exhibition in Virtual Reality (VR). The virtual training rooms foster the method of loci, a famous memory enhancement technique leveraging spatial memory. The rooms are deliberately very different from each other, including claustrophobic rooms, bright areas, or open spaces, to create a strong anchor for teaching content. In addition, the inherent stereoscopy of VR allows for more efficient presentation of spatially demanding knowledge, such as 3D coordinate frames or clearance monitoring.

This paper presents the innovative pedagogy of JIVE enabled by VR and its use for ISS training.

Keywords: Virtual Reality, Robotics, Training, Exploration, Astronaut.

Acronyms/Abbreviations

DCP: Display and Control Panel
DST: Dynamic Skills Trainers
DoF: Degree of Freedom
EAC: European Astronaut Centre
ERA : European Robotic Arm
ESA: European Space Agency
EVA: Extra-Vehicular Activity
GRAVI-T: Generic Robotics Augmented and Virtual Reality Integrated Training
GRT: Generic Robotics Training
ISS: International Space Station
JEM-RMS: Japanese Experiment Module Remote Manipulator System
JIVE: Joint Investigation into VR for Education
MRO: Mobile Servicing System Robotics Operator
NASA: National Aeronautics & Space Administration
OBT: On-Board Training
PCS: Portable Computer System
SPDM: Special Purpose Dexterous Manipulator
SSRMS: Space Station Remote Manipulator System
RWS: Robotics Work Stations
VR: Virtual Reality
XR: eXtended Reality

1. Introduction

The European Astronaut Centre (EAC) is the European Space Agency (ESA) center of excellence for human spaceflight. EAC supports the astronaut selection, training, medical care, and monitoring, as well as astronaut's families before and during each flight. The center also provides training to Ground Support Personnel for all European-built International Space Station (ISS) hardware, including ESA's Columbus laboratory and payloads. Additionally, EAC offers Public Relation assistance for human spaceflight, outreach, and educational activities.

Before going into orbit, ESA astronauts are trained in three stages:

- Basic Training focuses on the foundation needed for later training stages, after which the trainee is qualified as Astronaut. This stage lasts approximately one year.
- Pre-Assignment Training focuses on providing the trainee with more in-depth knowledge of the ISS and preparing the future crew member for critical tasks that require specific skills such as robotics activities or Extra-Vehicular Activity (EVA). The duration may vary from several months up to several years, depending on the astronaut's mission assignment.
- Mission Specific Training: at this stage, the entire training content is related to the preparation of the specific, planned tasks and experiments to conducted during their time in orbit.

To complement the ground-based training, On-Board Training (OBT) is used on-board the ISS for unplanned tasks or to reinforce proficiency in certain skills.

To advance human spaceflight, and to benefit astronauts, instructors, developers, researchers, and operators, EAC created the eXtended Reality (XR) Lab in 2015. From the beginning, robotic operations instructors collaborated with the EAC XR Lab to identify the areas of robotics training that could benefit from Virtual Reality (VR). Robotic operations on the ISS are a complex topic, as outlined in section 2. To ease the teaching of this technical topic, the Joint Investigation into VR for Education (JIVE) was initiated as a collaboration between ESA and the National Aeronautic Space Administration (NASA). The investigation focuses on two complimentary optimizations. On one hand, it aims to reduce the student contact time required to reach a given level of proficiency. In parallel, JIVE aims to strengthen student memorization of technical content using the method of loci.

JIVE is a project to identify, implement, and evaluate improvements in robotics operations astronaut training using VR. The concept and approach of these improvements via VR are detailed in Section 3. The resulting new software and teaching flow have been approved for astronaut training, and Section 4 reports on the delivery of this new robotics training to the first astronaut candidates. Section 5 presents the lasting impact of JIVE in human spaceflight training, and the future improvements currently under consideration.

2. Robotics on the ISS

2.1. Current ISS Robotic Systems On-Board

There are currently four robotics systems installed on the ISS [1]:

- The Space Station Remote Manipulator System (SSRMS, also known as Canadarm2), a 17-meter robotic arm with seven degrees of freedom (DoF) in revolute joints. The symmetry and geometry of the arm allow it to be relocated at various bases on ISS using a walk off technique similar to how a monkey swings between vines, grappling the new base with one end effector and releasing the old base with the other (See Fig 1. a).
- The Special Purpose Dexterous Manipulator (SPDM, also known as Dextre), a dual-arm robotic system used to perform ISS maintenance operations. This system is dedicated to handling smaller payloads and electronic components where SSRMS size and interfaces are not adequate. (See Fig. 1 b).
- The Japanese Experiment Module Remote Manipulator System (JEM-RMS) provides access to the Japanese Exposed Facility and a payload airlock. It may also be used to launch small satellites (See Fig. 1 c).
- The European Robotic Arm (ERA), an 11.3-meter manipulator with seven DoF in revolute joints, provides access to the Russian segment of the ISS. Like the SSRMS, ERA is designed to walk off between bases. The arm is currently in its commissioning and testing phase and will soon enter active operational life. (See Fig. 2.)

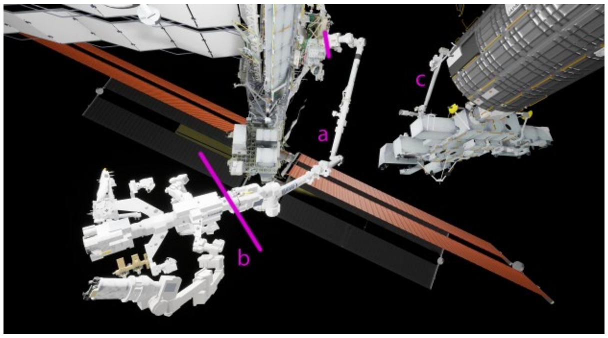

Fig. 1. Render of the SSRMS (a) with SPDM (b) attached to its tip. JEM-RMS (c) can be seen attached to JEM.

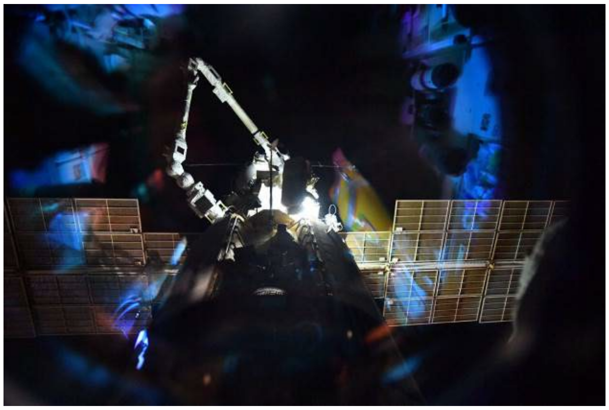

Fig. 2. ERA on the Russian Nauka module.

While on-board the ISS, astronauts interface with SSRMS more often than other robotic systems; nowadays, astronauts operate SSRMS for visiting vehicle capture and robotically-integrated extravehicular activities (EVA).

During those operations, crew interfaces with SSRMS from one of the two Robotics Workstations (RWS) located in the Cupola and the Destiny Module (US Laboratory) (See Fig. 3). Each RWS houses two hand controllers, three dedicated monitors that display external camera views, a laptop (Portable Computer System – PCS) to configure and command the arm, and a hardware panel (Display and Control Panel – DCP) for supplementary control of the arm and cameras. At the workstation, crew operators can fly SSRMS in different operational modes depending on the procedure or task. One of them, known as manual mode, makes use of an inverse kinematics algorithm to move the SSRMS tip; all the joints cooperate to maneuver the tip in a straight line. In comparison, single joint mode, another operational mode, allows the crew to command rotation of one joint at a time thanks to a direct kinematics algorithm.

Fig. 3. RWS in the ISS US Laboratory

As mentioned earlier, one of the two RWSs is located in the Cupola, a 7-window, dome-shaped observatory, which looks out on Earth and provides a partial view of the station. This view is advantageous for operations that require the SSRMS to capture visiting cargo vehicles. The windows of the Cupola serve to complement the cameras routed to the monitors at the workstation, maximizing situational awareness for operators. On the other hand, the RWS in the Lab (see Fig. 3) is prime for EVAs for two reasons; it is more spacious than the Cupola which is an important consideration for this six-to-eight-hour operation, and the Lab RWS allows for the use of additional camera views like crew helmet cameras for clearance monitoring. Understanding how to use multiple cameras to monitor SSRMS clearance from ISS external components is the most critical and foundational skill an operator must leverage during these operations to ensure the safety of the crew and the vehicle.

2.2. SSRMS Control Concept

Launched in April 2001, SSRMS was originally designed to be operated purely by trained astronauts via the robotic workstations. By February 2005, robotics flight controllers had developed tools and processes to allow for ground control of SSRMS from the Christopher Kraft Mission Control Center in Houston, Texas [2]. Since then, flight controllers have taken responsibility for most robotic operations which allows astronauts to dedicate more time to scientific initiatives and experiments. The two operations that are still reserved for crew operators are visiting vehicle capture and SSRMS-supported EVAs. Consequently, the required robotic training for crew has dramatically reduced over the years.

2.3. Training

Robotics training for the SSRMS still requires approximately two hundred hours of instruction. It is divided into four main flows:

- Generic Robotics Training (GRT), a mandatory component of the aforementioned Basic Training;
- Mobile Servicing System Robotics Operator (MRO) Training;
- Specialist Skills & Flight-Specific Training;
- On-Board Training.

NASA's robotics branch has over 20 years of experience in delivering technical content to the student and certifies ESA counterparts as GRT instructors for European Astronaut Corps. Historically, this training flow alone has taken between 20 and 30 hours for the student to complete. Upon completion of the classes, the astronaut student must pass a skills-based evaluation, which is assessed by a robotics instructor and senior astronaut. About five years ago when ESA approached NASA Robotics with a desire to develop expertise in VR, both organizations quickly identified GRT as a training flow that would greatly benefit. And thus, JIVE was born, and GRT was set to evolve.

GRT introduces foundational concepts that are then reinforced through hands-on, skills-based tasks in the Dynamic Skills Trainers (DSTs). These DSTs emulate the robotic workstations on board ISS with hand controllers and monitors. It is critical for the student to demonstrate understanding of GRT's fundamental teaching points before moving on to MRO training at the Canadian Space Agency. Without any required pre-requisites, GRT begins by familiarizing the trainee with external components of ISS to build the student's situational awareness and 3D mental map of the station. Then the lesson flow focuses in and reinforces specific robotics concepts, as described below:

- 3D visualization and location determination of the robotic arm motion using only three camera views;
- Collision monitoring, the ability to interpret camera views to verify that SSRMS is not colliding with ISS structure during motion;
- Parallax, a clearance technique used to monitor SSRMS motion with two cameras during close-proximity robotic maneuvers;
- Joint mnemonics, understanding positive and negative joint motion and being able to anticipate how SSRMS will move as a result;
- Manual commanding using translational and rotational hand controllers to maneuver the SSRMS to a target position;
- System configuration and efficiency to establish baseline expectations of procedure execution in a timely manner.

Historically, all classes in the training flows listed above were taught in the robotics workstation simulators (the DSTs) with hands on hand controllers (see Fig. 4). On the monitors in the DST, the student can select three cameras to view ISS and SSRMS and to support the assigned task. To visualize arm motion, the instructor would typically use a 3D-printed SSRMS model and coordinate frames, located in front of the student and to the right of the monitors, respectively, in Fig. 4. To create a 3D mental map of ISS components like modules, platforms, and antennas, the student iterates through exercises selecting different camera views on the flat, 2D monitors in the simulator. Simply put, the DSTs have physical constraints that are not necessarily as conducive to introducing students to the environment of robotic operations and foundational concepts as a virtual reality facility.

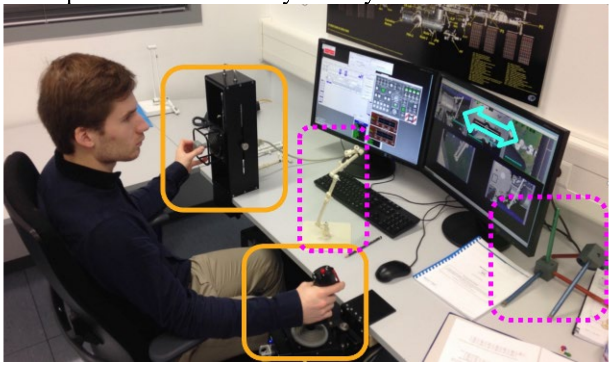

Fig. 4. Student in DST.

3. The JIVE software design

3.1. The teaching rooms

The method of loci (also known under a variety of other names, including the memory palace and the mind palace technique) is a memory enhancement technique [3] known since the ancient Roman and Greek civilizations. The method is centered around the idea of associating information with a place in an imagined visual environment to strengthen memory associations.

As this technique is used by most champions of the annual World Memory Championship, Krokos et al. [4] studied and confirmed the applicability of the method inside VR worlds. Building upon this innovative use of VR as a spatial memory helper, JIVE provides ISS teaching material in a singular, large-scale memory palace.

JIVE's teaching rooms implement the method of loci by spreading the teaching material across multiple display booths, each one teaching a singular concept. Each one of these booths contains an amount of information equivalent to a single slide on a classical presentation. As previously described, robotics operation training is a lengthy topic, therefore the displays booths are grouped together in various interconnected teaching rooms. This organization is analogous to the layout of a museum, where the student astronaut walks through the deliberately designed VR exhibitions, guided by a robotics instructor.

The virtual museum leverages the method of loci by only teaching a single idea at any one location in the VR environment. The student's mental map of the museum acts as the substrate upon which the knowledge is retained. It is therefore crucial that the design of the JIVE environment enables the student to create a museum mental map as easily as possible. Taking inspiration from [5], a few principles were applied:

- Rooms that resemble one another or that are near each other present similar topics. The opposite technique is also utilized: different teaching topics need to either look different or be far apart.
- Each teaching room must have a unique dominant color, visible from outside the room. This color coding helps the student (when standing in the central "Hub", the common area that connects all rooms in Fig. 5) to see the progression of the lesson.
- The layout in each teaching room and of the larger environment cannot be self-similar or have any symmetry. This avoids creating visual similarities between teaching places in JIVE.

Fig. 5. The JIVE Hub as seen from the location where the student begins upon launching the software. Multiple teaching room entrances can be accessed.

As each teaching room has a distinct color, it was decided to group the colors according to the type of teaching carried out. In JIVE, concepts are taught in rooms with shades close to red (See Fig. 6, 7, and 8). Facts to remember, relying on the student's raw memorization capability, are taught in colors close to blue, and procedural memory is taught in rooms in shades of green (see Fig. 9 and 10). To further distinguish the identity of these rooms, the red rooms were made indoors, with short perspectives and depths of view, while the blue rooms are outdoors, with far-reaching sights. The green rooms are designed in-between the red and blue rooms, as semi-open spaces. Lastly, rooms of similar color are differentiated through the curation of different moods, leveraging different materials and apparent softness. For instance, the "Parallax" room (See Fig. 8) is made of hard orange concrete and bricks, while the "Motion Frames" room is made of soft red-carpet flooring and curtains (See Fig. 7).

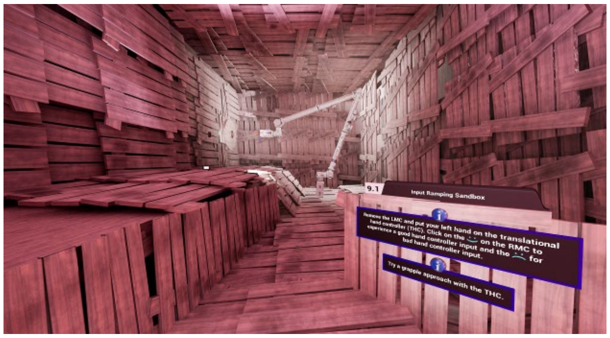

Fig. 6. The Input Ramping room.

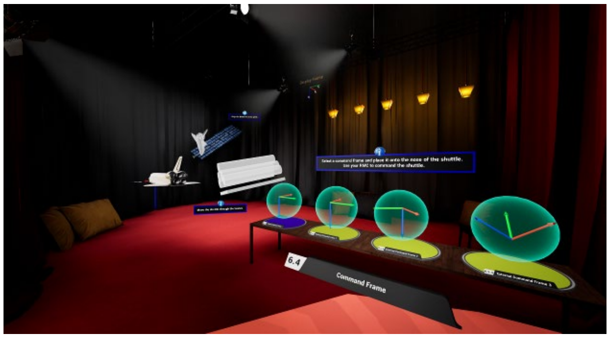

Fig. 7. The Motion Frames room.

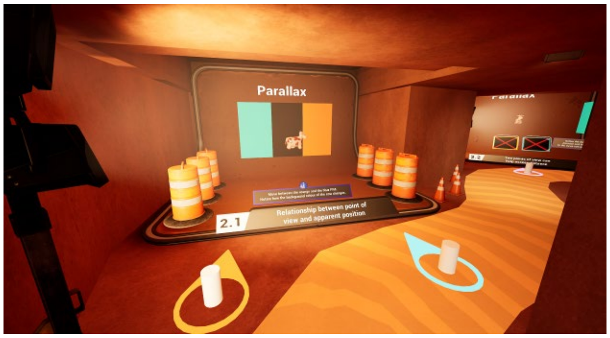

Fig. 8. The Parallax room.

Fig. 9. The Clearance room.

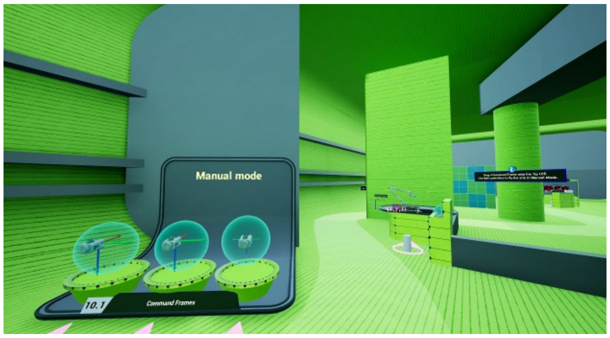

Fig. 10. The Manual Mode room.

Giving a visual identity to each room was an important element in JIVE's development. Great care was taken to set strong anchors for the student's memory, as per the "Intensity" principle of learning, described by [6], while not distracting the student from the technical concept. Repetition is another key aspect to the learning process; "things most often repeated are best remembered" [6]. JIVE uses content outlines and summaries before and after each teaching room (see Fig. 11), taking inspiration from the displays at the entrance of the test chambers from the Portal video game (as illustrated by Fig. 12). These outlines and summaries provide both structure and repetition during training delivery.

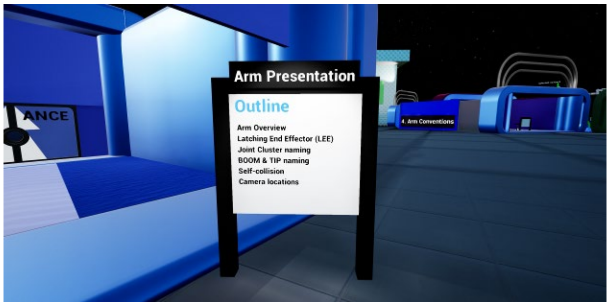

Fig. 11. The outline display near the entrance of the "Arm Presentation" room.

Fig. 12. The entrance of a test chamber in the Portal video game. These test chambers have been widely praised as an excellent video game tutorial. (Credit: Valve Corporation)

3.2 The ISS visualization tool

Interpreting camera views from the RWS monitors requires familiarization with ISS external components, as detailed in section 2. To reinforce visualization and understanding of ISS structure, JIVE incorporates an accurate 3D model of ISS in VR at a reduced scale, about five meters wide, as depicted in Fig. 13. The student can readily examine the fully detailed ISS model by raising, lowering, and walking around it. Furthermore, this smaller scale features higher effects of stereoscopy in human vision.

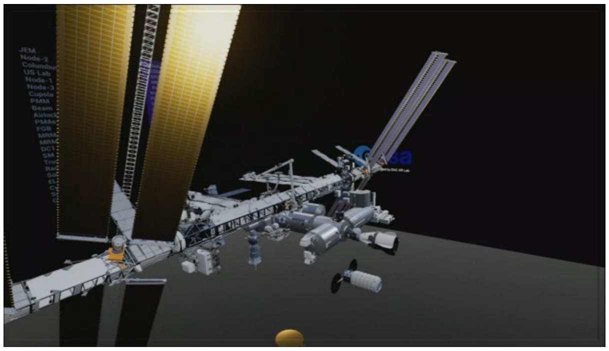

Fig. 13. Representation of the ISS in the JIVE-ISS VR application. Students can readily maneuver around the five-meter model.

The five meters ISS model also features interactive components. The student uses a pair of VR hand controllers, allowing to highlight/select individual modules of the station, or place floating labels on a set of points of interest. Students can also select and highlight the external ISS cameras (as seen on Fig. 14) to understand their positioning, orientation, and field of view.

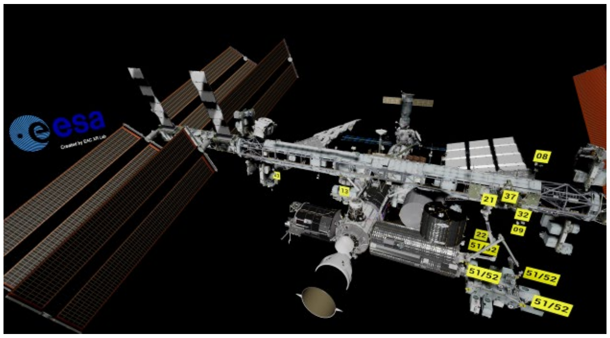
Fig. 14. Representation of the ISS in the JIVE-ISS VR application with camera number labels.

As a complimentary experience, the JIVE-ISS environment also includes a VR replica of the ISS at 1:1 scale; the student can teleport freely around its exterior to glean the full-scale size of various components. The student first arrives in a replica of the Cupola module, where Earth can be seen rotating below ISS. The camera monitors of the cupola have also been replicated, and the student can route various cameras to the monitors to apply what was learned from the small-scale ISS model. From there, the astronaut can teleport directly outside the station to fly freely around it.


Fig. 15. Life-size representation of the cupola of the ISS in the JIVE-ISS VR application. The robotics monitors are functional and display live views of the station's 3D model.

3.3 The lesson plan

Following a successful proof of concept for JIVE, NASA's robotics branch committed to a re-vamp and redesign of the GRT flow to incorporate VR. Leveraging over 20 years of experience in teaching technical content, NASA robotics instructors collaborated with ESA instructors to organize a new lesson chronology and seamlessly integrate the JIVE software. The new evolution of GRT is now known as Generic Robotics Augmented and Virtual Reality Integrated Training - GRAVI-T for short. Due to the hands-on nature of this training, there was careful consideration about how much time to spend in the VR facility and away from the hand-controllers in the DST. Considering the skills-based aspect to robotic operation, it was critical that the student still have ample opportunity to practice maneuvering and commanding SSRMS with flight-like hardware in the DST.

Thus, while all classes were originally taught in the DST, GRAVI-T is now designed such that the student is taught introductory concepts in VR and is then taken to the DST to familiarize him/herself with the hardware such as translation/rotational hand controllers and the Display Control Panel. After the workstation familiarization, the class location alternates between the VR facility and DST until the student begins their dry runs ahead of the evaluation. The evaluation itself is conducted in the DST with hands on hand controllers.

4. Results

4.1 First astronauts in VR training

NASA instructors iterated with ESA counterparts every step of the way to develop robust lesson plans and incorporate accurate models. They tested the VR environment and content through much of 2020 and 2021 in preparation for their first astronaut students. Some of the early test students included NASA flight controllers, Space Force personnel, internal robotics employees and interns. In December 2021, NASA announced the selection of 10 new astronaut candidates from a pool of 12,000 applicants. ESA is set to announce their own selection of candidates in 2023. As of August 2022, the first pair of astronaut candidates have been successfully trained and introduced to complex robotic operations via GRAVI-T and JIVE. Instructors and JIVE developers have been keen on collecting feedback from all students to continue building upon the manner in which this technical content is presented. Some early feedback from the students have included comments on how helpful the immersive environment is for learning ISS components, visualizing SSRMS motion, and understanding command frames and modes.

5. Conclusions

5.1 Discussion

JIVE approaches the use of VR for teaching in an unprecedented manner; the team has not found existing projects or work that combines the method of loci with museum architectural design theory. The resulting software delivers an explicit and tailored memory palace as a teaching backdrop. Furthermore, it is the first time a tool shows the ISS in VR to astronauts as part of their training.

Both ESA's and NASA's robotics instruction teams have adopted the software as a standard tool for their classes. Although only a couple astronauts have taken this modernized course, the feedback from everyone involved has so far been very positive and productive.

GRAVI-T students often praise the amount of visual context and the geometrical clarity of the explanations.

While it already delivers dividends, JIVE is the first steppingstone to introduction of VR in human spaceflight training. Numerous instructors, specializing in various other disciplines, have approached the EAC XR Lab to adapt JIVE's ISS VR visualization tool to improve their own lessons. With the growing popularity of VR, our workmanship with immersive technologies continues to develop, and further optimizations in human spaceflight will be unlocked. Teaching in a VR exhibition built like a memory palace can be applied in other contexts, and JIVE serves as the trail-blazing example for inspiration beyond ISS robotics training.

5.2 Future works

JIVE is a joint ESA-NASA investigation into VR for education, and the novel software described above is only a by-product of this collaboration - a particularly valuable by-product. JIVE will continue to foster the democratization of VR in human spaceflight training. The next topic for consideration is the integration of Human-Machine Interface flight hardware with the immersive software, as an effort to further merge the use of VR for skills-based robotics training.

Another topic of noted interest is extending the functionalities of the ISS visualization tool. The most immediate use-case is robotics, where the memory palace can embed the ISS and the Earth in full scale since the memory palace and ISS model currently exist as two separate environments. In VR, many optical illusions are possible and will remain unnoticed [7] or accepted under the student's suspension of disbelief. Perhaps a small cabinet door in the museum opens to a full-scale ISS in orbit around the Earth. After descending upon the model, the student could command the SSRMS from onboard the station for short exercises, merging active operation with the existing teaching rooms. The VR ISS visualization tool has applications in many other areas of ISS training. Various instructors are gaining interest in the tool, and the EAC XR Lab is currently assessing how to meet the growing demand.

In a more distant future, JIVE may extend its focus. Today it serves to improve lesson delivery time and memory retention. A reduction of training-related logistics and resource allocation could also be considered. There are currently inexpensive VR headsets available on the market that embeds a self-contained computing platform which would further reduce overhead cost by removing the need for a computer tower and wall sensors. If matured, the cost of the infrastructure could be divided by a factor of five or even ten. The co-location of the instructor and the student in the same facility may not be a requirement for conducting classes if a secure, internet-based, multi-user session can be established. Thus, the student and the instructor would only need to be available at the same time, while stress on facility allocation could be relieved. Lastly, using video game tutorials as a model, the requirement for an instructor's presence could be relaxed. Instructional messages could be delivered with audio-visual recordings, and the student's progress could be followed by state machines. These possibilities allow part of the training to transition to a self-study format, while keeping the other part with a human instructor for feedback and evaluation. Interacting with an instructor remains desirable to answer any questions the student may have, to add a learning flexibility beyond what a machine can allow, and to uphold that human spaceflight should remain, first and foremost, a human endeavor.

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