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User Interaction and Motion Dynamics Simulations for Microgravity — Development of a Concept and Prototype for Astronaut Training with Virtual Reality

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Abstract

Going forward with the requirements of missions to the Moon and further into deep space, the European Space Agency is investigating new methods of astronaut training that can help accelerate learning, increase availability and reduce complexity and cost in comparison to currently used methods. To achieve this, technologies such as virtual reality may be utilized. In this paper, an investigation into the benefits of using virtual reality as a means for extravehicular activity training in comparison to conventional training methods, such as neutral buoyancy pools is given. To help determine the requirements and current uses of virtual reality for extravehicular activity training first hand tests of currently available software as well as expert interviews are utilized. With this knowledge a concept is developed that may be used to further advance training methods in virtual reality. The resulting concept is used as a basis for development of a prototype to showcase user interactions and locomotion in microgravity simulations.

Keywords

Human Spaceflight; Virtual Reality; Astronaut Training; Learning; Educational Software

CR-Categories

Applied computing → Education → Interactive learning environments
Applied computing → Physical sciences and engineering → Aerospace
Human-centered computing → Interaction design → Interaction design theory, concepts and paradigms

1. Introduction

Construction for the International Space Station (ISS) began in 1998 and it was manned continuously from 2000 to today. With current plans dating the end-of-life of the ISS to the year 2030, space agencies like the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) are starting to expand their human spaceflight programs beyond low Earth orbit (LEO). In preparation for these new missions, ESA is investigating methods of accelerating and streamlining astronaut training. One of these methods is the use of

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Virtual Reality (VR) technologies. First, the context of the paper is described as well as the motivation behind the development of VR training simulations. Furthermore the goals of this work are outlined and the methodology used to achieve them. Finally, the current state of the art of microgravity motion and interaction simulation is examined and presented.

1.1. Motivation and Goals

For humans, space is a highly unusual environment, with varying gravity models ranging microgravity to reduced gravity levels on the Moon and Mars [1]. Furthermore psychological and physical stress induced by factors such as the dangers of spaceflight and living in close confinement with crew members of different nationalities pose challenges as well [1]. In order to train astronauts, many Earth based analog environments are utilized [1]. These analogs range from ISS module mockups to parabolic flights. Each of these environments convey varying levels of fidelity for different points of interest [1]. Currently, astronaut training for microgravity environment familiarization is carried out in two ways. The first method is the use of a neutral buoyancy pool. The focus of the neutral buoyancy training sessions, is to allow astronauts to get familiar with the locomotion in microgravity environments and learn the required tasks needed to carry out their extravehicular activity (EVA) [2]. In a neutral buoyancy pool, astronauts are usually equipped with a space suit or an analog thereof. They are then immersed into the pool, where mockups of ISS modules are featured. Using these mockups, a variety of tasks such as repairs, assembly and maintenance operations are trained [3]. However neutral buoyancy pools are limited in access, as they are often overbooked [2]. Furthermore Bolender et al. [2] describe that a training session usually requires the involvement of a Test Director, a Test Conductor, a Medical Doctor, a Safety Officer and an Audio/Video Operator. Additionally, there are at least one dive supervisor and six supporting divers involved. This large amount of staff required to safely operate a training session increases the cost of a training session is significantly.

The second method for microgravity environment familiarization are parabolic flights. Here, an aircraft climbs steeply before entering a parabolic arc. In this configuration, the passengers and any payload will experience microgravity, until the aircraft climbs out of the dive at the end of the arc [4]. In this setting, weightlessness lasts between 20-30 seconds [4]. While the physical fidelity of this method is very close to effects experienced during a spaceflight, the relatively short duration of each parabola limits the time astronauts can spend learning locomotion and interaction with the simulated microgravity environment. Furthermore the cost of a parabolic flight starting upwards of $5,000 per passenger is a factor to be considered as well[1].

In order to provide a more readily available and cost effective training method in comparison to both the neutral buoyancy pool and parabolic flights, VR technologies are proposed.

1.2. Methodology

In order to develop useful and accurate simulations for astronaut EVA training, first-hand experience from experts who will test the current state of the art of VR applications for microgravity simulations is utilized. Afterwards semi-structured expert interviews with closed and open questions will be held in order to capture test results as well as set requirements and evaluation goals for the interaction and locomotion concept and prototype to be developed in the course of this paper.

The objective of the expert interviews is to determine an outline of astronaut training as it is currently performed, what the goal of these training methods is, which tasks and interactions astronauts perform during EVAs and how they are limited by the environment and the EVA suit in performing these tasks and interactions. Furthermore, the interview

[1] gozerog.com/index.cfm?fuseaction=Reservations.welcome (Last access: 15. February 2020)

aims at discovering how and where VR training fits in the current training regime and what the expected benefits of VR astronaut training are. The experts consist of a range of astronaut instructors and engineers working at the European Astronaut Centre (EAC).
A total of 25 questions were defined by the author to determine an outline for a realistic training environment for development of a VR prototype. The questions were divided into two parts: The first part is focused on current EVA training and its goals as well as understanding specific task and interaction related aspects of EVAs.

The second part of the interview was aimed at the VR aspects of this work. To better understand the experts' opinions, as simple self-assessment of the interviewee's VR experience is requested. This is then followed by a series of questions related the most popular, currently available VR experiences that use microgravity locomotion in one form or another. The second half of questions aims to understand which aspects of EVA training may be best taught through VR training and why VR may be a suitable training tool. The final three questions determine the opinions of the interviewed experts on VR as a substitute or complementary method of training EVAs and where the added value of VR training lies.
The interviews were conducted in person with one interviewee and one interviewer respectively. The audio of the interviews was recorded temporarily and later transcribed in writing.

The ultimate scope of this work is indeed to investigate the locomotion and interaction techniques experienced and used by astronauts in real and simulated microgravity environments to define and outline a concept for a VR based motion dynamics simulation. The resulting concept may be used as a basis for development of a prototype to demonstrate the basic interaction and motion dynamics techniques. The development of the prototype will be carried out at the eXtended Reality Laboratory (XR Lab) laboratory at the EAC.

2. Basics

With the outline of this paper and methodology set, the basics for this work can be described. Human locomotion and interaction techniques used by astronauts in microgravity environments are described first. Second, the basic principles of human perception and learning, especially with regard to educational software and VR, are explored and analyzed. These are based on the results gained from the expert interviews.

2.1. Human Locomotion and Interaction in Microgravity and Training Methods

When humans move under the influence of a counterforce against gravity, such as the floor pushing up against a person, it is in our natural behavior to move by walking. However humans lack any motor skills for locomotion in microgravity, as true microgravity cannot be experienced on Earth. Even skydivers in free fall will experience drag which at terminal velocity acts as a counter-force large enough to stop the continuous acceleration towards the ground.
Therefor, in a microgravity environment, astronauts experience a highly unusual way of locomotion, mainly through the use of hand rails and foot restraints, which are found both inside and outside of the ISS [b]. Occasionally during an EVA, the astronauts are fixed to the end of the ISS Remote Manipulator System (SSRMS), in which case they are moved by a crew member from inside the ISS [b]. However the main methods of locomotion during EVAs consist of the use of hand rails for movement and tethers for safety [b]. For any self-induced movement, astronauts are typically tethered to the ISS with at least two tethers at any time. This is, because unlike the interior of the ISS, losing contact to the ISS would put astronauts in an extremely dangerous, potentially deadly situation [b]. In addition to these restrictions, astronauts need to keep their tools organized and in good working order while traversing on the exterior of the ISS [b].
While outside the ISS, astronauts are equipped with an EVA suit. Typically these

are the Russian Orlan or American Extravehicular Mobility Unit (EMU) space suits. The suits help protect the astronauts against the harsh space environment. They provide air pressure and oxygen supply high enough to support normal breathing as well as thermal control systems (TCS) to regulate body temperature. However, because of the protection they provide, they are bulky and difficult to use [b]. The movements of the space suit are heavily restricted and require considerable force to be performed [b]. Astronauts' abilities to move and interact with equipment and tools during EVAs are therefore heavily restricted. However the most profound effect on the interaction comes from the gloves [b], as these are the most used part of the EVA suit for interactions. One major constraint of the gloves is the significant reduction in haptic feedback to the astronauts [b]. This makes it difficult for astronauts to grab objects such as tools and handrails, as well as using tools. The latter is especially true due to the bulkiness of the gloves. In some cases it may prevent the hand from reaching into holes or underneath objects, where a gloveless hand would usually fit without issues [b]. However most repair and installation tasks that are performed during an EVA, including the tools used, are usually designed with these constraints in mind [a]. It is only when an unexpected failure occurs, that repair tasks not designed for EVAs have to be carried out [a]. The training for which usually takes place in the Neutral Buoyancy Facility (NBF) at the EAC or in the Neutral Buoyancy Laboratory (NBL) at Johnson Space Center (JSC) [a, b]. Here, astronauts wear special diving suits, similar to EVA suits used on the ISS. With these suits, limits in visibility and range of motion may be simulated [a]. The goal of these exercises is to familiarize astronauts with the EVA environment as well as the constraints they face while performing maintenance tasks outside the ISS [a, b]. Another method developed by NASA is the Active Response Gravity Offload System (ARGOS) [5]. ARGOS performs gravity offloading without having to immerse the astronaut into water. This allows for more accurate visual representations of the environment as well as the tools used for the specific task. Development of EVA tools follows a process of prototyping and iteration, which includes constraints present for terrestrial testing environments such as neutral buoyancy pools, NASA Extreme Environment Mission Operations (NEEMO) and ARGOS [6]. The constraints range from waterproofing to weighting and the fact that achieving weightlessness for prolonged periods of time is unfeasible on Earth.

2.2. Human perception and learning in the context of VR

VR technology is mainly a visual medium. Therefore, using visual learning and memorization practices is advantageous for VR implementations of educational software.
According to the definitions of teaching methods by Spalter et al. [7], VR technology would combine laboratory, visualization, simulation and lecture methods of teaching in one tool. While VR allows for immersion into the subject matter, this very immersion will often lead to significant work and cognitive overload in trainees [8]. A study conducted by Richards et al [9] concluded, that simply using VR as a means of training and teaching, does not inherently improve learning in itself. Such that simply presenting information on screen, wether this is on a PC monitor or in an immersive VR experience, does not implicitly improve learning [8, 9]. However both studies fail to make use of actual interactivity in the immersive medium. There are no methods for users to interact with objects within the scene, making the examined VR experiences simply passive video playback experiences, albeit in a 3D world with 6DOF.
Meyer et al. [10] shows that using immersive VR experiences for *pre-training* of trainees resulted in an overall significantly higher retention rate of gained knowledge, when compared to video lessons [10]. This suggests VR to be a useful tool for astronaut *pre-training and environment familiarization* and may be able to replace some currently used video and classroom lessons [b]. In fact, it is expected that 10-30% of all astronaut training may be conducted through VR technologies

in the near future [b].
One method of learning using visual methods is the memory palace technique, or Method of Loci (MOL), where a story or knowledge is built up through the use of an imaginary palace in which objects and symbols are placed in various rooms, each associated with a specific concept or idea [11]. With this method, early tests by Fassbender et al. [11] have shown that test subjects would retain information about 25% better when using the memory palace method as compared to a list of words. In a study with 78 participants conducted by Huttner et al. [12], users showed that in comparison to using a computer screen, users in VR would perform 5-7% better in retaining information. Furthermore the application of the MOL was significantly higher among VR users in that they were more inclined to make use of this learning method in comparison to the control group [12]. These results suggest that MOL and VR are well suited for each other.
A major benefit of VR technology is that it helps engage the trainee deep in the subject matter, provides new methods of presenting content and helps to preserve a consistent environment for learning for each trainee [13].

3. VR Applications for Microgravity Environments

Locomotion in microgravity environments has been explored in video games for a number of years now. For VR, there is a selection of games and experiences available, which allow the user to freely roam an environment in microgravity. In this section these games and experiences are examined, and their locomotive and interactive features with respect to EVAs are explored. Figure 1 shows the local coordinate system of an astronaut. Rotational motion around each axis is defined as follows: A rotation around the X as is pitching motion. Subsequently, a rotation around the Y axis is a roll maneuver and lastly a rotation around the Z is defined as yaw.

One of the earliest uses of VR technology for EVA training was the training used for the Hubble Space Telescope (HST) repair mission in 1995 [14]. The objective of this training application was to teach flight team members EVA procedures and how to operate HST hardware for the repair mission [14]. To achieve this goal, 3D representations of both the Space Shuttle cargo bay and the HST were modeled [14]. While wearing a Head Mounted Display (HMD), the users would maneuver through the virtual world by using two joysticks, one for translating and the other for yaw, pitch and roll control, allowing for a full six degrees of freedom (DOF) [14]. Moreover, no locomotion using hand rails or tethering equipment was modeled. As the focus of this application lays within the realms of knowledge transfer for flight team members and not astronauts [14], this was also not necessary.

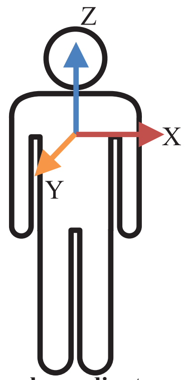

Figure 1: Local coordinate system of an astronaut [i]

In early 2017 the VR experience Mission: ISS was released for the Oculus Rift. The experience allows the user to freely explore the interior of the ISS as well as carry out an EVA and spacecraft berthing. The user is given a basic set of controls and locomotion techniques. While inside and outside of the ISS, the user may use the thumb sticks on the controllers to move around, similar to a flying motion or a virtual jet pack. Additionally, the user can hold onto any surface, handrail and object with a collision box around it. By releasing the contact point while moving the hand, the user can generate a forward momentum in the opposite direction. Loose objects such as condiment containers, cargo bags and tools may also be interacted with.

Figure 2: Mission: ISS (top left) [ii], BBC Home (top right) [iii], Lone Echo (bottom left) [iv]

The user can grab these objects and throw them. The exterior interaction follows a similar design. The user may hold onto hand rails as well as any collidable surface, while also being able to utilize a virtual jet pack to fly around the ISS. Locomotion is mainly based on the conservation of momentum. No roll control is provided to the users hand interaction as per the default setting. Much of the roll and pitch control is done by the second thumb stick control. However an optional setting is available that enables the user to use two hands for roll control. Yet no pitch control is available. The user may utilize pitch control by yawing 90 degrees to either direction and using a roll maneuver, then returning to the original yaw-orientation. The twin hand roll maneuver was perceived to be highly unpleasant during testing by experienced VR users and experts at the EAC's XR laboratory. The main complaint about the roll maneuver was related to its seemingly arbitrary point of rotation, which was perceived as unrealistic and confusing. At least one expert complained about headaches and nausea, directly related to the two handed roll maneuver. Furthermore it was not possible to physically push off the walls without grabbing them first. Although hands would collide with walls, they did not interact with them. Furthermore objects would not transfer momentum to the user, so that thrown boxes and other objects did not exert an equal and opposite force to the user, as it would be the case in reality. During an EVA the user is able to use hand rails to move along the exterior of the ISS.
However the user is not required to utilize a tether and can freely float away and perform maneuvers with the Simplified Aid For EVA Rescue (SAFER) to fly around the ISS model. The SAFER system is a jet pack attachment to the EMU suit that allows astronauts to steer back to the ISS in case they become untethered and start drifting away.

A second EVA experience was provided by BBC Home - A VR Spacewalk, released in late 2017 for the Oculus Rift. Here, the user is set out to perform a virtual spacewalk or EVA on the ISS to assess damages. While the locomotion system is similar to the one used in Mission: ISS, it feels much slower and less responsive to user-induced motion. Unlike Mission: ISS, the user cannot hold on to walls and other static objects. The only objects that can be held onto are handrails. When moving, the inertia of the user is accounted for, making acceleration slower than the actual hand movement. The user is however not able to roll or pitch. The only possible user motions are lateral. The game will determine roll and pitch based on the players location. This means, roll and pitch are on rails. Whilst this is an acceptable solution for a guided VR experience for inexperienced users, it is unsuitable for astronaut training or familiarization, as it makes locomotion unrealistic and limited.

Lastly, the VR game Lone Echo was released for Oculus Rift in mid 2017. Here, the user is given an extensive locomotion mechanic. The user's virtual body, represented by an inverse-kinematic-influenced 3D model, interacts with the virtual environment in a realistic way where walls can be used to push off from, as well as hand rails to hold on to and change direction. However the user is not given the option to induce a roll movement. Therefore the directions up and down stay the same throughout the game. This helps significantly with orientation. Furthermore, it reduces risk for potential motion sickness.

4. VR Interaction and Locomotion Techniques for Microgravity Training

Based on the current state of the art and the experience gained from testing the applications previously mentioned as well as from expert interviews, a concept for VR interaction and locomotion for microgravity training is proposed. The concept presented here will be developed under the project name Virtual Reality Extravehicular Activity (VREVA).

4.1. Interaction

ESA has developed the Joint Investigation into Virtual Reality of Education (JIVE) as a complementary method of astronaut robotics training. Because JIVE [13] is already in the evaluation phase and is likely to be introduced as an option for astronaut training shortly, the interaction techniques used in VREVA are kept as close as possible to the ones used in JIVE. These are for example the layout and mapping of the buttons used for various functions. This is for familiarity reasons, so that astronauts do not need to learn the control mechanisms of the new application all over again, and can easily transition from one to the other and back. This means, the main way of interacting with the environment will be through motion controllers that the astronauts use with their hands. Feedback is provided to the astronaut via vibrotactile signals from the motion controllers. This way, the user can recognize interactable objects and surfaces and can react accordingly. Providing this feedback to the user is a desirable feature that many of the tested games provide as well [d]. The feedback helps users recognize when an action can be performed and is the first step of the interaction between the virtual environment and the user. However it is not possible to keep all of the interaction designed for JIVE the same for VREVA. This is due to the constraint of microgravity locomotion. Where JIVE only utilizes one set of controls with a part of the controller using variable functions, this is not entirely possible in VREVA, because it utilizes two completely separate locomotion mechanisms. Therefore the general interaction using vibrotactile feedback for interactable surfaces and objects holds true, however the button mappings on the motion controllers differ when in microgravity-mode. Astronauts will ultimately learn to perform an EVA where they will use and interact with tethers, perform operations with tools and other equipment and control their space suit. These tasks include, but are not limited to, repair and maintenance work, installation of new systems and (passive) robotics operations.

4.2. Locomotion

While real microgravity locomotion allows astronauts to control all three rotational axes, roll, pitch and yaw, in VR this can lead to significant disorientation and motion sickness. As previously mentioned, roll maneuvers by the use of two hands were perceived as unpleasant by expert testers and the author, even leading to feelings of nausea and headaches. However, moving in this way is necessary and must be possible in the training simulator. Therefore it is desirable to allow users to adapt to this highly unusual form of locomotion by slowly introducing new techniques and maneuvers.

The main method of moving around outside of the ISS is through the use of hand rails. The astronaut can use their motion controllers to attach their virtual hands to these hand rails through the use of a grabbing action. By translating the hand in 3D space while grabbing, the astronaut is able to move themselves around the virtual space. If the astronaut lets go, the virtual body will continue to move at the same velocity and in the same direction as it was in the moment the astronaut released the hand rail. This is due to the conservation of momentum. During translation up/down or left/right in the real world, astronauts would experience a change in pitch or yaw angle respectively. This is due to the fact that the center of mass is not aligned with the motion of the hand. However implicit counteracting of this pitch is performed by an astronaut to combat this. Because in VR trainees are not able to hold on to a physical handrail, this implicit counteracting does not occur. An expectation that the translation will not induce a change in pitch/yaw angle holds true.

There are multiple ways to perform more complex maneuvers such as pitch and roll. One of these is the use of two hands to induce roll. However as described previously, in the VR experience Mission: ISS this was perceived as highly discomforting. To combat this, a dampening mechanism as well as a continuation of the translation mechanism may be used. For pitch and yaw, a two handed approach may also be useful, however it would also be possible to implement a yaw and pitching maneuver that increases with distance to the trainee's body. When the trainee is holding onto a handrail and their arm is close to their bodies, yaw and pitch maneuvers may be turned off completely, as to keep the expectations mentioned previously. As the trainee moves their arms further away from their bodies, pitch and yaw motions may be activated, increasing in effect for larger distances. Which of these approaches is most useful and least discomforting, may only be evaluated after implementation and respective testing with trainees and experts.

4.3. Self-perception and embodiment

Humans perceive their own body at all times, mostly implicitly, but often actively. Most notable are hands and arms, as almost every task humans perform involve hands within the peripheral vision. Our bodies give us a lot of information regarding position in space and ability to perform actions [15]. Perceiving your own body in VR can be done using an avatar, a virtual representation of a body. The amount of control over the avatar is directly linked to the feeling of presence within the simulation [15]. Furthermore presence is in turn directly linked to how well learned information is retained over extended periods of time [10]. For this reason it can be concluded that a well controlled avatar increases information retention rates for human locomotion training in microgravity environments. Therefore, an avatar is required for VREVA, that can be controlled by the trainee. This can be achieved in two ways. The first is using inverse kinematics (IK), where the location of the avatar's limbs, such as arms, elbows and legs, is calculated based on the position of the VR controllers. In the second approach, the limbs may be tracked with additional VR trackers. This method is more accurate in representing limb location however it involves more hardware and is therefore more costly and complex to use. A study by Schramm [15] finds that there is no significant difference in perceived embodiment from using IK versus tracking. While IK allows for joint limits to be set for a space suit, as this would be the case in reality, the same cannot be done with trackers in software alone. While trackers are more accurate, they would require an exoskeleton to act as a limiting mechanism for joint movements. While such an exoskeleton exists, it would need to be modified with trackers added to serve this function. Two arguments underline the use of exoskeleton. An exoskeleton provides accurate physical feedback to the trainee, which can provide an additional sense of realism. Secondly, its tracking markers can be fixed to the structure, allowing for more precise tracking of the limbs.

4.4. Learning

As outlined in chapter 2 an approach to VR education using MOL yields in good results for information retention. For this reason, VREVA will implement a similar concept to the ones mentioned previously. Additionally, the ESA developed JIVE training tool implements this principle as well [13]. JIVE presents the topics in different ways ranging from self-study to goal-oriented approaches [13]. They are presented in an abstract form so that the knowledge gained by trainees is generic enough to be reused in future robotics projects beyond the ISS [13]. For VREVA a similar approach is chosen. A museum-like building structure is created, in order to fulfill the requirements of the MOL. In this, every room will represent a different subject matter, divided into stations to be completed by the trainee. Each lesson will introduce new concepts consecutively. Besides the locomotion and interaction aspects to be taught as mentioned in the previous sections, it is also important to teach the trainees about the environment [c]. This environment is the exterior of the ISS. While it is not important to model the ISS to the highest degree of detail in general, it is necessary to convey accurate representation of objects and surfaces astronauts will interact with, as they will later recall this information during their EVAs [b]. Furthermore, familiarization with the environment includes introduction to tools and techniques to be used during an EVA, as well as the EVA suit, which astronaut trainees will need to familiarize with.

4.5. Physiological aspects

During VR training it is possible that trainees will experience discomfort with the equipment. Possible issued range from the heat of the HMD and possible receivers and batteries, to the overall weight resulting in neck strain [d]. Moreover the effects of VR sickness are well known today and range from simple discomfort and eye strain to extreme cases of headaches and even vomiting [16].

These factors have to be considered in the development of VREVA, as rooms and lessons have to be completable within an hour. It is possible that lessons in microgravity locomotion have to be considerably shorter than an hour, due to the fact that the unusual method of moving and the lack of inertial feedback can cause discomfort to a much higher degree than the teleportation locomotion present in JIVE [13]. To determine this, it is necessary to develop and evaluate a prototype that showcases the basic functionality.

5. Prototype Development

The concept presented in this work is used as a basis for development of a prototype for astronaut microgravity training, developed at ESA's XR Lab at the EAC. The prototype was developed using Unreal Engine 4.24 (UE4). In order to provide future projects with a platform, the development of the prototype followed a modular approach. The two main modules consist of generic items as well as project specific items. This guarantees that generic items such as the control and interaction scheme described in section 4 can be adopted by any future project. A development method like this is highly desirable among the interviewed experts, as it is a form of standardization that helps accelerate development processes in the future [b]. The hardware used for the development consisted of an HTC Vive Pro HMD and two controllers. Additionally, the HMD was equipped with a wireless setup.

As described previously the concept divides controls into the generic controls which are similar to the ones found in JIVE, and the microgravity mode controls. An unmapped button in the JIVE control scheme was used to allow switching between the two modes at any time. As described in the concept, the MOL will be used to teach the trainees. Three levels were built for this purpose. The main map, known as the hub, serves as the persistent map in UE4. The other two levels are a suit familiarization room and a microgravity testing room. Both are built to showcase the basic functionality of the prototype. The suit familiarization room implements the IK used for manipulating the suits joints. The general idea is that trainees are able to familiarize with the restrictions and joint limits of the space suit. A trainee may pick up the gloves and shoes of the suit to move them. Using IK the suit responds accordingly and the joints will bend as far as the limits will allow them. UE4 implements two types of IK solvers. The first being the FABRIK solver, developed by Aristidou et al. [17]. The second is an implementation of CCDIK as proposed by Wang et al. [18]. As the purpose of the space suit familiarization lesson is to allow trainees to experience joint

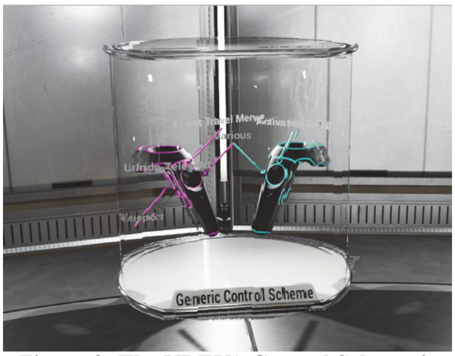

Figure 3: The VREVA Control Scheme is presented to the user inside the application [v]

restrictions of a space suit, the CCDIK implementation was chosen, because it is the only available UE4 IK solver that implements joint limits.

The microgravity testing room consists of a small confinement for testing the locomotion and a basic mockup of the ISS module Columbus with handrails. In microgravity mode, the trainee is only able to grab handrails. Flat surfaces are cannot be grabbed. Yaw is provided to the user through the HMD, translation by using the hand controllers while grabbing onto a handrail. To grab a handrail, the user must squeeze the grip buttons of the HTC Vive controllers. Figure 3 shows the control scheme as it is presented to the user in the virtual environment. Pitch and roll have not yet been implemented for this prototype.

6. Discussion and Future Work

While neutral buoyancy training offers high fidelity in terms of locomotion, it lacks significantly in the visual aspect, as the training is carried out by mid to low fidelity mockups of the ISS modules [3]. In contrast, VR applications are capable of delivering high fidelity in the visual realm. However, in return they cannot deliver the same level of sophistication for locomotion simulation, since the user is confined to virtual objects. By using an exoskeleton, some physical feedback can be given to the trainee.

For these reasons, a VR application may only be used as a complementary method of training, alongside conventional training methods. However the availability and accessibility of VR is a significant factor. ThereforeVR training may be able to replace some instructor lead classes and video based training. Another aspect to be considered when comparing neutral buoyancy and VR training is that EVA hardware is often designed and tested in neutral buoyancy pools [6]. In order to perform these tests, each tool must be physically built [6]. Using VR to test some design aspects of the tool may help accelerate its development, considering that the 3D Computer Aided Design (CAD) models created for the prototype manufacturing process may also be used in a VR environment.

The prototype developed in this paper shows the basic functionality of the concept defined. Continuing this work, an evaluation needs to be performed to find issues and improvements to the concept. Furthermore an extended feature set will have to be defined, including course work and lessons planned. Some of these may include generic familiarization with the EVA environment, the training of safety procedures such as tethering and rescue operations, generic maintenance tasks and tool usage [d]. After the review phase is completed, a full training simulator with all the functionality described in this concept.

7. Summary

Current astronaut training methods for microgravity involve a large number of instructors, supporting staff and specially equipped facilities. They need to be planned long in advance and are inflexible and costly. In order to mitigate these issues, complementary training methods such as VR training can be utilized. In this paper an overview of the requirements to develop a VR training system for microgravity is outlined by utilizing expert interviews. For these interviews 25 questions are defined that investigate different aspects of EVA training and VR applications. Furthermore, an analysis of human locomotion in microgravity and human learning in the context of VR educational applications is given. Using MOL as a learning environment is determined to be a good fit to teach astronauts using VR. A test survey for current microgravity locomotion experiences is carried out. Three applications are then evaluated by focusing on their strengths and weaknesses.

The concept presented in this paper outlines and defines a method of implementing microgravity training simulators. It covers aspects from interactions and locomotion in microgravity, educational software in the context of VR and physiological aspects of trainees. A first prototype was developed using UE4, along with an HTC Vive Pro HMD and wireless setup. The prototype implements a control scheme similar to the one used for JIVE. This is done in order to provide control scheme familiarity across ESA's training simulations. User feedback on interactive surfaces is provided to the trainee via vibrotactile feedback from the HTC Vive controllers. Microgravity locomotion is performed through the use of hand rails. Translations are performed using the hand controllers. Yaw control is provided by the user. IK is used to provide a space suit joint limit familiarization demonstration. A full training simulator will be developed in the future and it will include all the findings of this work. Thus, a complete test will be done to assess the final result.

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10. Interviews

a. A. Drepper, interview by author, Cologne, 09. March 2020

b. R. Seine, interview by author, Cologne, 12. March 2020

c. S. Ghiste, interview by author, Cologne, 17. March 2020

d. L. Ferra, interview by author, Cologne, 02. April 2020

11. List of Figures