X-ARM: A NOVEL ARM EXOSKELETON COMBINED WITH EXTENDED REALITIES TO TRAIN FUTURE ASTRONAUTS

Andres Martin-Barrio*, Guillaume Fau, Mathieu Deremetz, Tigo Van Roy, Raphael Boitte, Ernest Porqueras-Codina, Antoine Bayou, Guilhem Le Carrour, Valentin Vial, Pierre Letier, Jeremi Gancet[1] and Cristian Englert[2]

[1] Space Applications Services NV/SA., Leuvensesteenweg 325 1932 Sint-Stevens-Woluwe. Belgium, * amb@spaceapplications.com
[2] European Space Research and Technology Centre (ESA - ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, Netherlands.

ABSTRACT

A growing number of space travellers is anticipated in the first half of the 21st century. However, current tools for astronauts are not well adapted to the requirements of training a large number of individuals for microgravity environments. The X-aRm project offers a novel immersion experience aimed at preparing future space visitors. Combining an arm exoskeleton with Extended Reality technologies, this project provides multi-modal stimuli to enhance the feeling of presence during the training process. The primary purpose of the exoskeleton is to offer force-feedback to the user. Through a careful redesign process, it prioritizes robustness, comfort, and responsiveness, resulting in significant improvements over previous iterations. Functioning as a technology demonstrator, this device is driven by three custom-designed Brushless DC motors and integrates two passive degrees-of-freedom. The bilateral communication between the exoskeleton and the virtual world allows users to experience the forces involved in different activities of typical Extravehicular Activities, such as pushing and pulling from handrails in microgravity. This innovative strategy replicates the movements of trainees and the constraints of wearing a spacesuit in real time, assisted by gravity compensation technologies. As a result, future training facilities leveraging this technology are expected to require less supervision and occupy a smaller, while also providing higher immersion, flexibility, scalability, customization and safety.

1. Introduction

The outer space is commonly perceived as one of the most hazardous environments for human beings. Various factors contribute to this perception, including space radiation, absence of air pressure and gravity, extreme temperatures, meteorites and orbital debris, closed or hostile environments, changes in Circadian rhythms, and many other issues related to physiological disorders [1, 2]. Human evolution has historically been shaped by the living conditions on Earth. Consequently, preparing humans for microgravity conditions or the exploration of other planets, by mean of adequate training, is critical for successful human spaceflight.

Nowadays, the training of astronauts relies on a wide range of courses and facilities to prepare them for any situation they may encounter in space. This preparation includes exhaustive education in science, medical procedures, languages, and survival training, among others. Various technologies are used to make astronauts familiar with the space environment, such as real-size mock-ups, parabolic flights, air bearing floors, gravity compensation devices, and neutral buoyancy facilities, among others [3]. The combination of these training technologies has successfully prepared multiple generations of astronauts. However, these assets lack flexibility to customize the training process, and are limited in scalability to accommodate an increasing number of trainees [4].

Interestingly, many of the technologies used to train astronauts involve manipulation and navigation tasks that require force feedback, which is crucial for the learning process. Previous studies have emphasized the importance of force feedback for multiple critical training tasks in space [5]. Astronauts heavily rely on the sense of force for numerous activities in the space environment. For instance, astronauts aboard the International Space Station (ISS) use a spacesuit called the Extravehicular Mobility Unit (EMU) to perform installation or maintenance tasks known as Extravehicular Activities (EVA). During these missions, astronauts navigate in the space environment by pushing and pulling from handrails, experiencing inertial forces derived from their mass, or performing mechanical tasks using Pistol Grip Tools (PGT).

The hypothesis of this work states that the use of multimodal stimuli from Virtual Reality with exoskeleton devices to train future astronauts provide a higher flexibility, scalability, customization, safety, and immersion compared to traditional training methods. The following Section 2 will introduce previous works in this domain to understand the context of the proposed implementation.

2. State-of-the-art

Astronaut training has evolved to incorporate advanced simulations, microgravity adaptation, teamwork, physical conditioning, and specialized skills. Simulation-based training uses spacecraft mock-ups and realistic scenarios for tasks like docking and emergencies. Microgravity training, through parabolic flights and underwater simulations, helps astronauts prepare for weightless environments and extravehicular activities. Crew resource management training emphasizes teamwork, while physical fitness routines counteract muscle and bone issues caused by microgravity. EVA training uses underwater and virtual reality simulations for spacewalk practice. Language, cultural, and medical training ensure effective communication and health management. Digital learning platforms enhance flexibility, and interdisciplinary skills ensure astronauts are equipped for diverse challenges in space exploration [6].

Extended Realities (XR) can offer perception deception technologies able to create a feeling of immersion using virtual elements and spaces. XR devices usually encompass Head Mounted Displays (HMD) and other multi-modal devices for this purpose. For example, Virtual Reality (VR) provides a completely enveloping virtual environment; Augmented Reality (AR) overlays virtual elements onto the natural world; and Mixed Reality (MR) allows virtual elements to interact with natural ones in real-time [7].

Perception deception, as a neuroscience field involving controlled manipulation of sensory inputs, could benefit astronaut training by replicating the unfamiliar and challenging conditions of space. By simulating altered gravity, distorted spatial orientation, and sensory shifts, trainees could develop adaptability and problem-solving skills. The visual reorientation problem is a phenomenon that frequently occurs in the space environment when the perception of an object changes due to the shifting visual field and cues [8]. Additionally, the same approach can enhance psychological resilience, prepare for motion sickness, and improve decision-making under stressful situations, better preparing astronauts for the disorienting experiences of space travel [9].

Astronauts depend significantly on their sense of force for a multitude of tasks within the space environment. Therefore, exoskeleton devices have also been proposed for this purpose, like *Mindwalker*, a brain controlled lower limbs exoskeleton for rehabilitation with potential applications to space [10]. Also, an upper limb exoskeleton for reduced gravity training using spring-based parallelogram mechanisms as passive gravity compensation [11]. Other researchers introduce a low-cost exoskeleton countering gravity using unique control methods, exhibiting promising results for simulated gravity resistance [12]. In addition, it is worth highlighting an innovative hand exoskeleton that compares hard and soft actuation and sensing systems for Extravehicular Activities in Space [13]. Or the design of a high-quality haptic arm exoskeleton for training and rehab in virtual environments, considering diverse constraints and requirements for effective rehabilitation and training [14]. Despite the efforts, there are no exoskeletons customized to space training combining a good performance, transparency, robustness and comfort.

Some technologies developed by Space Applications Services (Belgium) are precursors of the present work. *EXOSTATION* is a 7 degree-of-freedom (DoF) anthropomorphic wearable arm interface for manipulation and operation tasks [15]. *ICARUS* is the next version, made sturdier, lighter and included a hand interface [16]. *SPOC* is another version with eight actuated joints and a four-channel control architecture to perform bilateral teleoperation. *DEXROV,* proposed dual exoskeleton arms and hands to study the viability of Remotely Operated Vehicles (ROV) for deep-sea inspection [17]. Moreover, EXOSUIT is the latest project that used the previous exoskeleton and adapted it with Virtual Reality to train astronauts [18]. These exoskeletons, despite their numerous advancements, were built using capstan-based technologies, which introduced inherent maintenance complexity and lacked emphasis on comfort and sturdiness. Now, the X-aRm exoskeleton emerges providing a new actuation system while offering higher robustness, reliability and comfort. Following Section 3 explains its implementation.

3. Implementation

This section summarizes the main technical developments of the X-aRm project. The objective of this European Space Agency (ESA) funded initiative is to develop a flexible, scalable and immersive technology demonstrator to train the upcoming generations of astronauts. A novel exoskeleton design is proposed based on custom, brushless direct current (BLDC) motors to provide high reliability, robustness and force-feedback transparency. This exoskeleton, combined with a VR headset, ambitions to create a multimodal setup that will blend multiple stimuli to increase the perception of users and reduce the training reality gap. The following sections detail the situations in which this system is anticipated to contribute.

3.1. Use cases

Since the second half of the 20th century, more than 600 people have crossed the altitude of space. Most of them are assigned to microgravity research and space station operations in microgravity. One of the most critical tasks are the EVA, in which astronauts repair equipment, conduct experiments or perform maintenance tasks. Thus, this is the main training use case as suggested by ESA for the X-aRm project.

Besides, motivated by the NASA Artemis program that aims to reestablish a human presence on the Moon, the second use case of X-aRm will preliminary tackle the challenges of manipulation tasks under reduced gravity.

3.2. Architecture

X-aRm follows a teleoperation architecture that handles how to control the exoskeleton remotely. The objective is to provide the user an interface that represents the information in an intuitive way. The proposed teleoperation system relies on a bilateral communication (Figure 1). In other words, a *VR Simulation* represents the virtual movements, which are determined by the exoskeleton pose and interface buttons, managed by the *Control* module. At the same time, the *VR Simulation* and the *Haptics Engine* generate soft and stiff forces that are applied to the exoskeleton. The *VR Simulation* has been developed using Unreal Engine 5 and is able to generate forces with slow response times like inertial ones when pushing or pulling from a handrail in microgravity. However, this software cannot compute collisions at high frequencies, necessary to emulate fast-response forces like contacts with the environment. Thus, the Chai3D *Haptics Engine* is synchronized with a replica of the VR Simulation to compute such forces. All these commands are sent to the *Control* module while a *User Interface* has also been developed to configure, command and monitor the performance using a web-based application.

All the communications are handled by a custom Server that centralizes the data in an efficient manner using TCP-IP. The fast-response, stiff forces must handle high frequencies of 1000Hz to be considered as real-time. Slower-response forces can be handled with frequencies of 60-100Hz like the inertial ones when making displacements in microgravity. Other type of slow-response force is the spring-effect in the elbows due to the inflation of the spacesuit or EMU. In other words, the nature of the forces draw the real-time requirements.

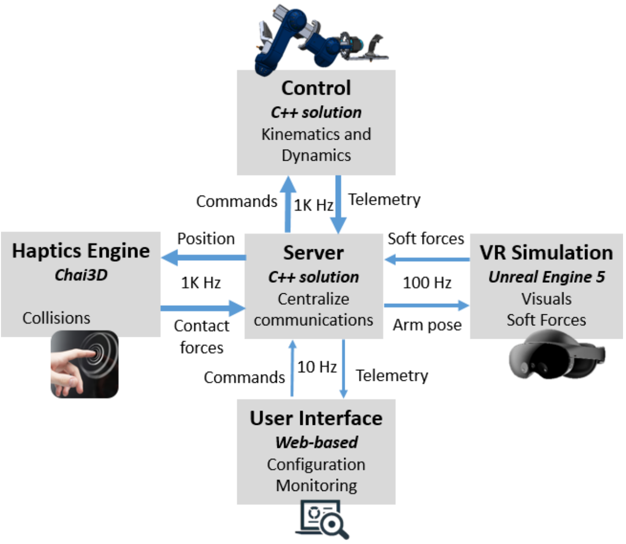

Figure 1: X-aRm software architecture diagram

3.3. Exoskeleton Design and Control

The X-ARM project developed an anthropometric exoskeleton as a robust technology demonstrator with core design focus on transparency and comfort (Figure 2).

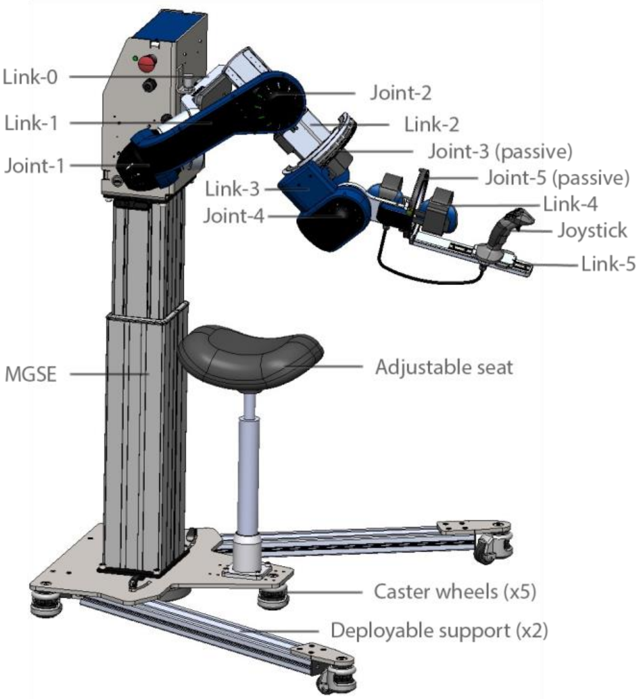

Figure 2: Computer model of the X-aRm exoskeleton

The exoskeleton is set in a *Mechanical Ground Support Equipment* (MGSE) and covering 5 degrees of freedom including shoulder, upper and lower arm motions. It is designed with five revolute joints according to the symmetric configuration $R\perp R\perp R\perp R\perp R$, where R indicates a revolute joint and $\perp$ the orthogonality between two successive joint axes. Joints 1, 2 and 4 are actuated while joints 3 and 5 provide passive sensorized feedback to the system motion controller.

Each of the articulated links are assembled around a rigid aluminum frame for robustness and surrounded by a protective 3D printed casing. The structural parts of the exoskeleton are made of aluminum 7075-T6. For ensuring material compatibility and protection from environment conditions, the parts are anodized. The casing has been manufactured using *Selective Laser Sintering* (SLS) 3D printing with *Polyamide* (PA) material. Each parts of the casing were then painted and varnish for protection. The top parts of the casing can be open to access directly all internal electronics components during the system validation tests and for maintenance.

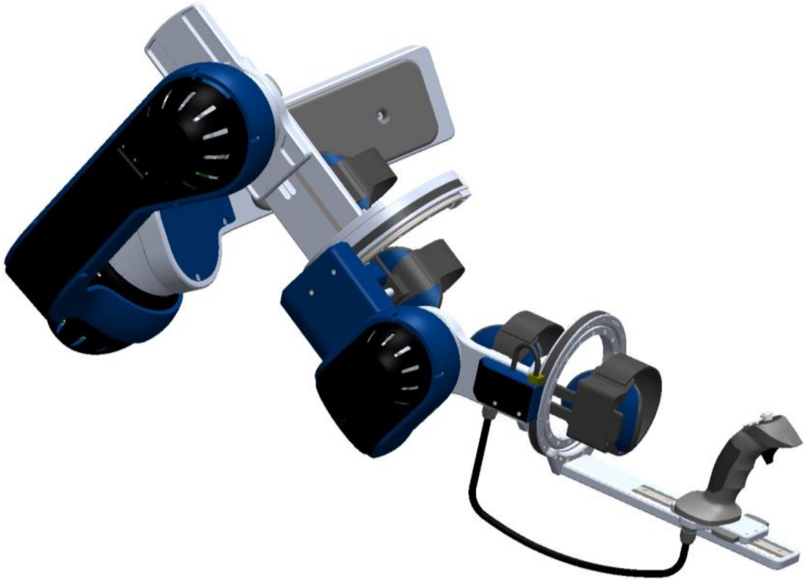

Figure 3: X-aRm exoskeleton. Technology demonstrator with 3 active degrees-of-freedom and 2 sensorized joints.

Two active joint sizes have been custom-designed and implemented in the exoskeleton (see Figure 4). A heavy-duty one (87Nm) for joint 1 and joint 2 (shoulder active joints) and a small duty one (28Nm) for joint 4 (elbow active joint). These joint are derived from a series of robotic actuators initiated and developed by Space Applications Services in the scope of European space projects [19] and [20].

Active joints are composed of a BLDC frameless motor coupled with a Harmonic Drive transmission. The joint includes mechanical, structural and guiding parts that ensure the correct functioning of each element independently and as part of an assembly. Integrated *Hall*, incremental, absolute and torque sensors features the joints for control purposes. The joint has a hollow shaft for hosting cables inside the exoskeleton structure.

Figure 4: X-ARM hardware integration. Link 1 (left) and small and heavy duty joints (right)

Following the compact and integrated design, all the controllers of the motors have been disposed locally near each joint. Each active joint is fitted with a set of identical electronics parts: *Capitan XCR-E* motor controller with imbedded EtherCAT module; a RGB LEDs module to display status; and custom-made interface board modules for the BLDC sensors.

The link-to-link power and data harness is composed by multi-core, sleeved and meshed cables for mechanical protection and *Electromagnetic Interference* (EMI) grounding. They are carrying a 48V power bus and an EtherCAT communication bus connected to the local motor controllers. An isolated *Safe Torque Off* (STO) bus, also popularly known as *dead man's switch*, is integrated in the link-to-link harness as safety measure.

The main power (EU national grid 50Hz 230VAC) is provided through a single power line. It is then distributed to the electronic column control unit, to the *On Board Computer* (OBC) power brick and to the arm ACDC module. The main ACDC is powering the full arm at 48V 6A. The output power is protected by a main Emergency button or E-STOP, and with a green LED for direct visual ON/OFF feedback.The OBC is an NUC 11 from Intel that offer a double network connectors interface. It will support the internal control, and handle the communications with external devices like the laptop hosting the simulation.

Regarding the ergonomic aspects, three segments of the exoskeleton frame can be adjusted to the user's body arm and wrist size variance. The system is designed to host a wide percentile range P10-P95 of adult European Male/Female body size. Spring loaded and self-locking buttons must be pressed together to release the adjustment. If only one button is pressed, the adjustment link remains locked. This is a safety feature to prevent uncontrolled unlocking and change of link's length during operations. The pins will self-lock after release.

The interface with the arm is attached to the structure by two comfortable paddings and two Velcro straps: one for the forearm and the other for the upper arm. The paddings are wrapped around the user's arm and are secured by two soft Velcro. The user are able to strap themselves to the exoskeleton without need of external support. The Velcro should be tightened until a firm (but not strong) grip is obtained. The main padding and the straps can be directly removed and washed for hygiene.

Users can also decide whether they prefer to use the system while seated or in a semi-standing saddle seat with the back spine straight. The second option is recommended for a higher immersion in microgravity and for longer and more comfortable trainings. Two support frame elements can be deployed on the side of the MGSE to increase the stability of the system. These elements can then be folded to reduce the footprint of the setup for an easier relocation using integrated caster wheels.

The low-level control strategy for the exoskeleton arm encompasses *Proportional-Integral-Derivative* (PID) control, directly delegated to the *Ingenia* servo drives, with each control loop (current, torque, velocity, and position) meticulously fine-tuned for optimal performance. Executing these control laws directly on the servo drives offers distinct advantages, eliminating constraints imposed by communication protocols and mathematical computations, enabling operation at significantly higher rates, up to 40 kHz. This enhances user comfort and system efficiency.

At the high-level control, the serial chain of the exoskeleton is managed from custom kinematics and dynamics algorithms, offering features like active gravity compensation. These algorithms continuously adjust torque outputs based on sensed gravitational forces, offloading the user's arm weight to ensure representativeness of the environment. Consequently, the gravity compensation also reduces fatigue, optimizing user mobility and comfort during prolonged use.

3.4. *Virtual Reality Simulation*

The X-ARM exoskeleton, previously introduced, will be interconnected with a Virtual Reality simulation to create a feeling of immersion though perception deception. The exoskeleton will provide force-feedback based on the interaction of the user with this virtual environment. At the same time, the simulation will provide visual, aural and vestibular feedback to users.

This simulation environment has been created using *Unreal Engine 5.1*, allowing the representation of multiple complex geometries powered by the *Nanite* technology. The VR headset selected for this activity in 2023 is the *Meta Quest Pro* for its screen resolution and *inside-out tracking*, allowing an easy and standalone usage. It connects to the Unreal Engine simulation wirelessly through the *OpenXR* framework and using the *AirLink* technology.

Realistic and updated engineering models of the ISS, a rigged-exoskeleton of the EMU with constraints, or tools like the PGT have been imported and adapted to the needs of the EVA use case for VR. A tutorial has been created showing the user how to move their right arm with the exoskeleton and the left one with a VR controller using *Inverse Kinematics*. In addition, it trains the importance of always being docked with a safety tether to the station handrails, how to move around pushing and pulling from structural elements in microgravity, perform maintenance tasks with the PGT or manually launch a small *CubeSat* to orbit. As mentioned in Section 3.1 a preliminary demo has also been developed to show the difference of forces and gravity on the Moon surface. For this use case, a realistic landscape has been reconstructed from height-map images from the *Lunar Orbiter Laser Altimeter* (LOLA) satellite and processed for their use in VR.

Figure 5: X-ARM Simulation of the EVA use case for VR applications, showing how the astronaut grabs from a handrail in the Columbus module of the ISS.

The forces generated by the simulation are: *Inertial forces*, understood as those needed to counter the own mass of the trainee after performing displacements with the arms; and the *Spring Effec*t, torque applied to the elbow involved as result of the inflation of the EMU. However, the simulation does not generate *Contact forces*, result of touching the surface of structural elements due to the high frequency requirements. Thus, a Haptics Engine has been used as explained in the following section.

3.5. *Haptics Engine*

In our research, we employed a haptics engine to generate contact forces for the exoskeleton arm, a critical aspect of enhancing the tactile perception of users and overall experience. In choosing the appropriate haptics engine, we opted for *CHAI3d* over alternatives such as *H3D* due to several compelling reasons. CHAI3d's suitability stemmed from its robustness and ease of integration with our exoskeleton arm system. Its versatile open-source framework allowed for seamless customization and adaptation to our specific requirements. Moreover, CHAI3d's active user community provided invaluable support and a wealth of resources, simplifying the development process.

The VR Simulation environment and the Haptics Engine environment have been carefully synchronized and aligned for a smooth integration. Additionally, it is worth highlighting the significance of frequency requirements to generate Contact forces. Thus, our choice of a haptics engine capable of generating forces at a minimum rate of 500-1000Hz was instrumental. These high-frequency forces are crucial for providing real-time feedback to the user's sense of force, enabling them to perceive object shapes and dynamic interactions accurately. This fidelity in force rendering is paramount in ensuring the effectiveness, stability and safety of the exoskeleton arm, particularly in tasks that demand highly dynamic control such as the EVA use case with astronauts in microgravity.

3.6. User Interface

The objective of this *User Interface* (UI) is to provide an intuitive and flexible interface to interact with the exoskeleton. It allows users to configure the hardware, monitor all the sensor data and command different testing functionalities.

The UI has been designed as a web-based application using OpenMCT, an open-source framework developed by NASA, which provides tools to visualize data in real time or in history, handle events and create customized interfaces or plug-ins [21]. This solution is cross-platform and can be used on any device with browser like tablet or PC. It has been design following the principles of clarity, concision, familiarity, responsiveness, consistency, aesthetics, efficiency and forgiveness.

The UI is divided in 4 sections: *Configuration*, to change the settings of the hardware like the kinematic, dynamic or safety parameters; *Commanding*, to run pre-defined experiences or send commands for testing; *Monitoring*, to visualize the readings of position, torque or temperature sensors, among others; and *Terminal*, to track the state of previous commands sent by the UI and categorized as Pending, Failed or Success.

A *Unified Robotics Description Format* (URDF) has also been implemented in the Monitoring menu to allow a real-time representation of the exoskeleton in 3D. Raw data from sensors is sent and parsed in real-time to the UI to accurately represent the pose of the robot. It is possible to interact dynamically with this representation by moving, rotating and zooming in and out (Figure 6).

Figure 6: User Interface. Testing screenshot of the monitoring menu.

4. Results

By the time of this publication, the system is undergoing functional tests prior its final integration and validation. However, some results can be summarized from the current developments.

We have found that direct actuation using BLDC motors is well suited to reduce maintenance and increase reliability, compactness, transparency and robustness. In addition, the multi-point contact Velcro straps and fabric padding have proven to be comfortable enough to increase the use of the system for longer periods compared to previous setups [17, 18]. The materials and detailed design of the exoskeleton need to be carefully selected and planned to find a good compromise between mass and robustness. Otherwise, as in every serial robot, higher masses require more powerful actuators that are also heavier, ultimately leading to a *positive feedback loop*. In addition, the use of spring loaded and self-locking buttons has demonstrated to be very useful, user-friendly and robust to easily adjust the exoskeleton to the arm of each user.

Software applications capable to generate high-frequency forces to simulate contacts with surfaces do not usually provide the same level of visual realism, tools or VR compatibility as game engines like Unreal Engine. Thus, the use of *Chai3d* as haptics engine was decided. The use of Unreal Engine version 5.1 and its VR-compatible components *Nanite* or *Lumen* considerably leveraged the performance while keeping a high visual realism. The use of the Meta Quest Pro as standalone VR headset has proven to be more convenient than lighthouse-tracking solutions. However, the software connectivity or the battery duration were not always ideal. In a rapidly evolving context, new generations of more advanced and comfortable headsets are recommended for future works.

The main limitation of the presented work is that the exoskeleton was designed to be a Technology Demonstrator, purposely featuring 3 DoF instead of 7 DoF as desirable to provide force-feedback in the full arm kinematic chain. However, it shall help us validating that the selected technology is well suited to the next generation of training oriented force feedback exoskeletons. For the EVA use case, the next generation of exoskeleton would ideally have two fully actuated arms, extending the setup proposed in this work, and two additional hand interfaces with force feedback. With the upcoming interest in planetary exploration, legs exoskeletons and a vestibular platform, combined with the arms, hands and VR headset, would be ideal to train astronauts performing complex, combined manipulation and locomotion tasks under different gravity conditions.

Figure 7: Integrated X-aRm system with different candidates validating comfort, adjustability and portability.

5. Conclusion

In summary, X-ARM is a technology demonstrator that shows how state-of-the-art actuation based on custom BLDC motors, an improved structural design, a new arm interface and multiple software improvements made a force-feedback training exoskeleton more robust, transparent and comfortable compared to previous iterations [17, 18]. The hardware and software design has been customized to the needs of astronaut training including the desired session duration, the EMU constraints, the magnitude of the forces generated, the gravity compensation control, the seated configuration or the immersive VR use cases developed.

The hypothesis of this work as stated in Section 1 is that the use of multimodal stimuli from Virtual Reality with exoskeleton devices to train future astronauts provide a higher flexibility, scalability, customization, safety, and immersion compared to traditional training methods. Some of these insights need to be validated with relevant individuals like ESA astronauts and instructors. However, preliminary results show that the hypothesis is correct.

Simulation and Haptic engines have been developed flexible software strategies to allow a fast creation and edition of virtual environments easily. Therefore, unprecedented levels of flexibility and customization are granted. In addition, compared to more conventional training techniques like real-size mock-ups, parabolic flights, air bearing floors, or neutral buoyancy facilities, the X-aRm system stands out to have a smaller footprint and lower associated cost, making it an interesting solution with a larger number of trainees. In addition, X-aRm has been designed with safety as paramount criterion, holding different hardware and software layers of protection against undesired outcomes. Finally, the combination of all the visual, aural, vestibular and force-feedback stimuli lead to a perception deception effect in users and increasing user experience quality. Consequently, the X-aRm concept emerges as a promising tool to effectively train the nest generation of astronauts.

Acknowledgements

The X-aRm project has been funded by the European Space Agency (ESA) under the contract No. *4000138082/22/NL/GLC/ov* and coordinated by the Virtual Environments and Human-Machine Interaction (VEHMI) Team of Space Applications Services NV/SA (Belgium).

6. References

1. Löbrich, M. and P.A. Jeggo, *Hazards of human spaceflight.* Science, 2019. **364**(6436): p. 127-128.
2. Evans, S. *Space environment hazards*. in *43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. 2002.
3. Rönkkö, J., et al., *Multimodal astronaut virtual training prototype.* International Journal of Human-Computer Studies, 2006. **64**(3): p. 182-191.
4. Jones, H. *The recent large reduction in space launch cost*. 2018. 48th International Conference on Environmental Systems.
5. Gancet, J., K. Chintamani, and P. Letier. *Force feedback and immersive technologies suit (FITS): an advanced concept for facility-less astronaut training*. in *International symposium on artificial intelligence, robotics and automation in space, Turin, Italy*. 2012.

6. Seedhouse, Erik. Prepare for launch: *The astronaut training process*. Springer Science & Business Media, 2018.
7. Martín-Barrio, A., et al., *Application of immersive technologies and natural language to hyper-redundant robot teleoperation.* Virtual Reality, 2020. **24**(3): p. 541-555.
8. Tamaddon, K. and D. Stiefs. *Embodied experiment of levitation in microgravity in a simulated virtual reality environment for science learning*. in *2017 IEEE virtual reality workshop on K-12 embodied learning through virtual & augmented reality (KELVAR)*. 2017. IEEE.
9. Wilson, C.J. and A. Soranzo, *The use of virtual reality in psychology: A case study in visual perception.* Computational and mathematical methods in medicine, 2015. **2015**.
10. Gancet, Jeremi, et. al.. "MINDWALKER: a brain controlled lower limbs exoskeleton for rehabilitation. Potential applications to space." In *11th Symposium on advanced space technologies in robotics and automation*, vol. 1, pp. 12-14. 2011.
11. Jiang, Yifan, and Bing Qiao. "An Upper Limb Exoskeleton Design for Reduced Gravity Training of Astronauts." *Transactions of Nanjing University of Aeronautics and Astronautics* 35, no. S1 (2018): 27-34.
12. Wang, Yingxue, et. al. "Design and Verification of an Active Lower Limb Exoskeleton for Micro-low Gravity Simulation Training." In *International Conference on Intelligent Robotics and Applications*, pp. 114-123. Cham: Springer International Publishing, 2022.
13. Freni, Pierluigi, Eleonora Marina Botta, Luca Randazzo, and Paolo Ariano. *Innovative hand exoskeleton design for extravehicular activities in space*. Springer International Publishing, 2014.
14. Gupta, Abhishek, and Marcia K. O'Malley. "Design of a haptic arm exoskeleton for training and rehabilitation." *IEEE/ASME Transactions on mechatronics* 11, no. 3 (2006): 280-289.
15. Letier, Pierre, Elvina Motard, and Jean-Philippe Verschueren. "EXOSTATION: Haptic exoskeleton based control station." In *2010 IEEE International Conference on Robotics and Automation*, pp. 1840-1845. IEEE, 2010.
16. Govindaraj, Shashank, et al. "The icarus project-command, control and intelligence (c2i)." In *2013 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, pp. 1-4. IEEE, 2013.
17. Gancet, Jeremi, et al.: Dexterous undersea inspection and maintenance in presence of communication latencies." *IFAC-PapersOnLine* 48, no. 2 (2015): 218-223.
18. Martin-Barrio, Andres et. al. *EXOSUIT: a Training System for Future Astronauts based on an Exoskeleton and Mixed Reality*. 72nd International Astronautical Congress (IAC-21).
19. Mathieu Deremetz, et al. "*MOSAR-WM: A relocatable robotic arm demonstrator for future on-orbit applications.*" 71st International Astronautical Congress, IAC 2020. IAF, 2020.
20. Mathieu Deremetz, et al. "*Concept of operations and preliminary design of a modular multi-arm robot using standard interconnects for on-orbit large assembly."* 72nd International Astronautical Congress, IAC 2021. IAF, 2021.
21. Trimble, Jay, and George Rinker. "*Open source next generation visualization software for interplanetary missions.*" In 14th International Conference on Space Operations, p. 2348. 2016.