Using eXtended Reality as Digital Twin for Training and Collaboration: the FLEX-XR case study

Abstract — More than fifty years ago man first set foot on the moon, followed by six more successful crewed missions to the lunar surface. The last crewed mission dates back to 1972, after which interest in moon exploration diminished. Renewed interest in lunar exploration and colonization sparked the development of the Lunar analogue facilities (LUNA) at the ESA's Astronaut Centre (EAC) in Cologne. Part of LUNA is the Future Lunar Exploration Habitat (FLEXHab), which will serve as a simulation habitat to train for future lunar missions. In order to maximize efficiency and flexibility in the use of FLEXHab, the user should be able to familiarize themselves with the simulation before entering or during the utilisation of the facility. Extended Reality (XR) is expected to provide these benefits with a low-cost solution. The FLEX-XR project goal is to showcase possibilities of Virtual Reality for user familiarisation with the FLEXHab facilities, as well as support them in their experiment design process, by creating a digital twin of the facility and some of the intended experiments. This digital twin will consist of a Virtual Reality (VR) application allowing users to prepare for their experiments (e.g. laboratory lay-out, required instruments and wiring) and to train as a group, with a focus on familiarizing these users with the facility. At a later stage, an Augmented Reality (AR) application will also be developed to offer just-in-time and just-in-place information, procedures and data streams, while working in the real FLEXHab. Cooperation with ground support can also be facilitated by this AR application. FLEX-XR aims to demonstrate the added value of VR- and AR-applications for future lunar missions.

1 Introduction

Recently both NASA and ESA have renewed their efforts to explore the moon [1, 2, 3, 4, 5, 6]. ESA and DLR are therefore developing an analogue lunar training facility (LUNA) to train astronauts for future missions. LUNA includes a simulated lunar base, called FLEXHab, in which scientific experiments will be conducted [7]. In order to maximize efficient use of the FLEXHab, NLR has developed a VR-application for familiarisation with the FLEXHab and to assist users of the FLEXHab in the design of their experiments.

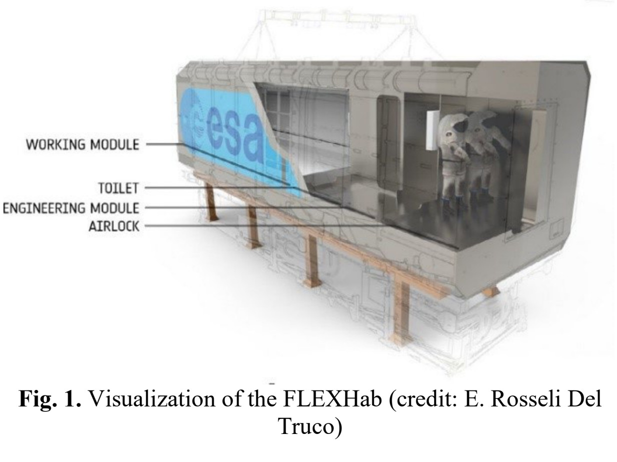


Fig. 1. Visualization of the FLEXHab (credit: E. Rosseli Del Truco)

1.1 Training and designing with XR technologies

Training methods currently used for space are based on technology developed between 10 and 20 years ago. This technology has proven to be safe, reliable and valuable, however it lacks flexibility and has high maintenance costs [8]. Innovate technologies, such as Virtual Reality (VR) and Augmented Reality (AR) provide the flexibility needed, are less maintenance intensive and are lower in cost [8]. Additionally, learning experiences can be enhanced through immersion and (remote) collaboration with others. AR and VR environments are progressively being integrated into space programmes aimed at crewed missions [9, 10, 11, 12, 13, 14, 15, 16].

VR and AR offer valuable training solutions for pre-defined procedural tasks. However, AR/VR also provide multi-user environments enabling remote collaboration in real-time, which highly reduces travel costs. In the case of FLEXHab, it allows users to test and validate experiment designs, choices and assumptions, before implementing hardware. It enhances communication because of the possibility to see the actions of others, their impact and providing a means to consult each other. This result in improved efficiency, designs and products.

1.2 Aim

The FLEXHab eXtended Reality (FLEX-XR) project is a collaboration between ESA, DLR and the Royal Netherlands Aerospace Centre (NLR). It aims at advancing interactive and collaborative training technology by developing and evaluating a new training framework for users (e.g., researchers, astronauts, and industrial partners working with FLEXHab) using AR and VR tools. More specifically, it aims to demonstrate how VR and AR technologies can be applied in familiarising users with a new environment such as FLEXHab and facilitate collaboration between these users. The project is divided into two phases. Phase 1, as described in this paper, focuses on the creation of a VR FLEXHab digital twin aimed at allowing users to design and configure scientific experiments. Phase 2 focuses on the creation of an AR application to support users in setting up and performing the experiment in the physical FLEXHab.

As part of phase 1, a FLEX-XR demonstrator has been developed. The demonstrator focusses on the design process which is typically an iterative and collaborative process. Specifically, the aim of the demonstrator is to support a creative and informed experiment design process by visualizing the environment and facilitating remote collaboration between multiple users.

This work describes the FLEX-XR demonstrator, its functionalities and potential in advancing XR training and experiment design technologies. In section 2, the software implementation and hardware used for the FLEX-XR demonstrator are described. In section 3, the functionalities of the application are listed. Conclusions and recommendations for further developments are outlined in section 4.

2 Methods

2.1 Hardware considerations

The FLEX-XR application can be run on multiple computers within IP reach simultaneously, so that users can work together. A basic computer including a network interface is required to run the application.

The application can be run in both conventional and VR-mode. In conventional mode, visuals are presented on a standard flat screen monitor and the user can interact with the application using the mouse and keyboard. For the VR-mode a VR-headset and controls are necessary to see and interact with the FLEX-XR environment.

The HTC Vive Pro headset was used to develop and test the VR application. However, the application is device agnostic. As such, the application interfaces with the device through the SteamVR platform, so any other VR sets compatible with SteamVR should work to full potential as well. Note that to run the VR-mode the computer hardware must be able to support VR-devices.

2.2 Software considerations

The Unity game engine (version 2019.4.18 LTS) and Visual Studio 2019 were used to develop the application using C# programming language.

For the architectural design, a Scriptable Object design (see Fig. 2) was chosen [18]. As a result, only a few modules and objects in the scene have any direct reference to other objects. The benefit being that various functionalities of the application can be organised into different, completely independent, modules. Thus, providing more flexibility and maintainability of the application.

Independent modules include, for example, the FLEXHab environment model, a networking module enabling users to work together, a functionality which allows users to install power cables, and a player menu where a user can browse the catalogue or enable various functionalities of the application (further details in section 3.3.). There is only an indirect reference between the modules, allowing them to function independently from one another.

Initially, there are only non-interactable items present in the scene providing the user with a 'blank canvas'. All interactable objects can be placed in the virtual environment via the instrument catalogue (see section 3.3.1.).

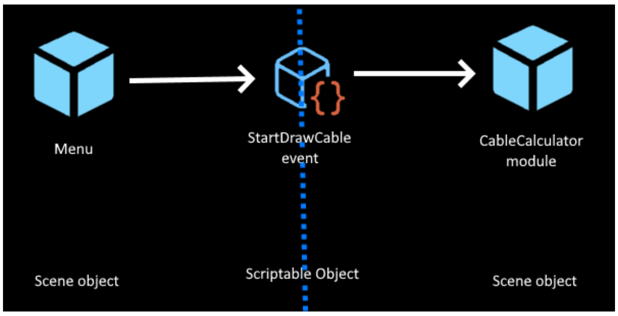


Fig. 2. Illustration how scriptable objects are utilized in the software application

3 The FLEX-XR demonstrator

3.1. Use Case

The FLEX-XR application is a demonstration VR and AR technology in the design of scientific experiments focused on lunar exploration. It goes beyond traditional applications, such as a step-by-step maintenance trainer, in that it allows the user to collaboratively set-up, iterate, and configure scientific experiments in a VR-environment. As such, the VR application has been developed based on a user scenario into which a team is able to configure and plan a scientific experiment within FLEXHab (see Fig. 3). Users could be scientists but also external parties such as research institutes or industrial partners.

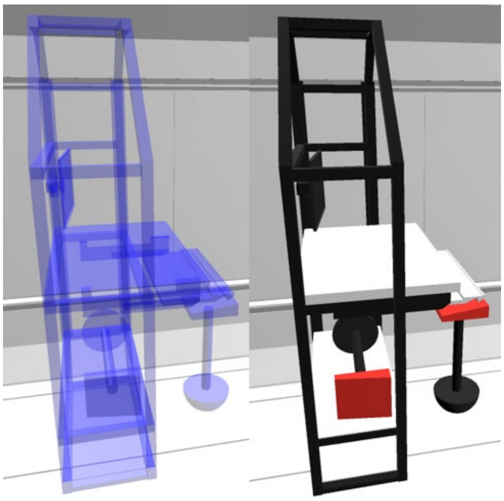


Fig. 3. A FLEXRack in the VR environment of FLEX-XR. Left: visualisation of a FLEXRack when it is being moved by the user. Other (remote) users would see the blue outline as well. Right: A FLEXRack as it is shown when it is placed inside the virtual environment.

Users can design and configure an experimental set-up in the VR-application together. Multiple instances of the application can connect to a local or remote network, so that team members do not necessarily need to be in the same physical location. Users also benefit from being able to see and verify if specific physical or power constraints have not been violated by an experiment configuration, without physical access to relevant hardware. Users could, for example, check whether a certain set-up would physically allow operators to access a FLEXRack or certain instruments. Moreover, they could verify that the power consumption of a certain configuration does not exceed the maximum power of the FLEXHab or estimate how many and what length of cables is required to run their set-up. FLEX-XR should allow users to check assumptions made about the physical environment without needing to actually set up the experiment. Consequently, FLEX-XR will arguably save time and improve the efficiency of the decision-making process in designing a scientific experiment in the FLEXHab.

3.2 Three demonstration experiments

As FLEX-XR is a demonstrator, the application's content has been limited to one scientific domain relevant to lunar exploration, namely astrobiology. More specifically, three kinds of astrobiology experiments, meteoritics, microbiology, and plant growth in low gravity [21], have been used to define the instrumentation included in the application. The next sections briefly describe an example of each type of experiment.

The instruments typically required to perform all three experiments are included in a virtual catalogue in the FLEX-XR demonstrator. For example, models of different sorts of microscopes, ranging from a relatively simple light microscope to a scanning electron microscope have been included for the user to select.

3.2.1 Meteoritics

The goal of a generic meteoritics experiment is to perform a chemical analysis of meteorites found on the lunar surface for understanding its evolution. After samples from the lunar surface have been retrieved, a meteoritics experiment typically consists of five steps, [22]:

1. Clean samples using a liquid bath.
2. Characterize samples using a scanning electron microscope.
3. Fragment the sample.
4. Analyse the sample with a microprobe.
5. Store data on a computer or hard drive.

3.2.2 Microbiology

The microbiological experiment usually aims to investigate the survivability of microorganisms in space for supporting the Panspermia theory [19]. To conduct this type of experiment the following steps are required:

1. Prepare two sets of microorganisms (i.e. test and control).
2. Expose one set to harsh conditions such as UV radiation, desiccation, or low temperatures.
3. Expose the other set to "normal conditions".
4. Monitor the conditions and intermittently perform measurements to measure growth (Colony-Forming Unit – CFU counting).
5. Store data on a computer or hard drive.

3.2.3 Plant growth in low gravity

Regenerative biological life support that uses plants are a likely option to supply future astronauts with essential resources such as water and oxygen. To maximize the efficiency of such systems, more knowledge on how plants are affected by low gravity conditions is needed. The experiment in the demonstrator investigates whether a French marigold can grow in lunar soil, and generally consists of the following steps [20]:

1. Retrieve lunar soil from the surface.
2. Treat the lunar soil with microorganisms to improve its fertility.
3. Install growth stations and monitor conditions.
4. Grow the French marigold.
5. Sample the soil and analyse microorganisms mutations.
6. Store data on a computer or hard drive.

3.3 Scenario steps and application functionality

Users of the VR-application can go through four steps to configure and plan their experiments and are supported by three aids, that assist them in the process (see Fig. 4). Specifically, these steps are:

Step 1 – Select research domain: users can select the research domain for the experiment they want to design. Based on the selected research domain, instruments will be recommended to the user.

Step 2 – Select instrumentation: users can select and spawn virtual instruments in the VR-application and can place them in space and/or on FLEXRacks.

Step 3 – Configure instrumentation: users can rearrange the placement of instruments or FLEXRacks freely to determine the most optimal configuration. A cable calculator, spatial constraint warning, power monitor, and planning tool can be used to assist them in the process.

Step 4 – Create time schedule: when the users finished the configuration of instruments, a planning tool can create a time schedule to provide them with an estimate on the preparation time required to set-up the experiment.

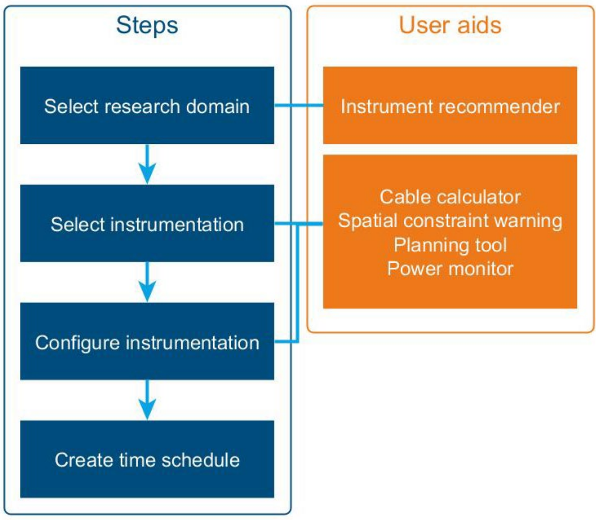


Fig. 4. The user scenario steps and application functionalities of the VR-application.

3.4 User aids

Five user aids have been implemented in the FLEX-XR demonstrator and these will be discussed in the following four sections. Note that the spatial constraint warning (section 3.4.3.) and the planning tool (section 3.4.4.) are currently under development.

3.4.1 Instrument catalogue and recommender

Users can access a catalogue (see Fig. 5) containing pre-configured FLEXRacks or individual instruments. Instruments contain a thumbnail, name, and description. Users can also select how many items they would like to add to the virtual FLEXHab. The catalogue will recommend instruments based on the selected research area, by placing them at the top of the list. Once instruments are spawned, users can drag and place these, in order to configure the experiment set up. FLEXRacks are limited in their placement, as they can only be placed against the wall, along predefined rails. Instruments can be placed anywhere in the scene and on the FLEXRacks.

Fig. 5. The instrument catalogue as it is shown in FLEX-XR. Recommender instruments are shown at the top of the list. Below, the user can page through all the instruments and on the right the user can add selected items to the VR environment.

3.4.2 Cable calculator

The cable calculator menu is used to draw power lines from wall sockets to instruments, or between instruments (see Fig. 6 top). Users can select the cable diameter, the minimal bending radius, and colour; they are free to choose the cable route.

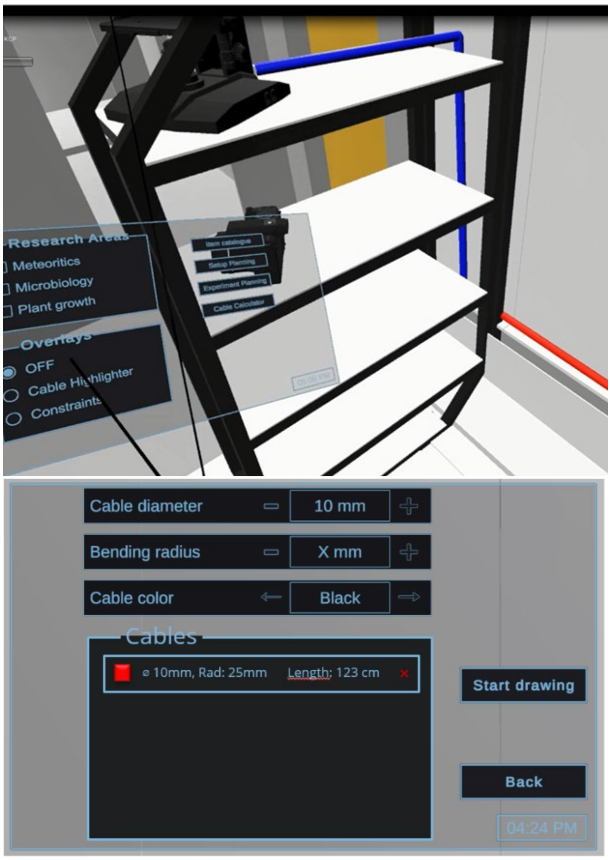
The cable calculator menu also shows an overview of all cables drawn (see Fig. 6 bottom). The length of the cable will automatically be calculated using the cables already added by the user. This overview can assist the user to estimate how much cabling is required to set-up the experiment in a specific configuration. Cable management is a major concern in space exploration. This feature can help to mitigate this concern by accurate preparations.

3.4.3 Spatial constraint warning

Certain instruments might have spatial constraints, i.e. they should be placed away from walls due to heat dissipation or they require clear space above for proper access. If these spatial constraints are not met, they will set off a warning which can be viewed via a monitor shown on the FLEXRack. This also shows the instrument power consumption in the FLEXRacks (see section 3.4.5.).

3.4.4 Planning tool

The planning tool aims to assist users in the planning real-world experiment set-up. Each instrument has an associated pre-defined set-up time, all of which add up to a total set-up time. Certain instruments require two people to configure, which imposes some planning constraints. These constraints will be visualized in the planning so that sub-tasks can be distributed across users, generating an optimal set-up plan.



Cable diameter 10 mm

Bending radius X mm

Cable color Black

Cables

🟥 ⌀ 10mm, Rad: 25mm Length: 123 cm ×

Fig. 6. Visualization of the cable calculator. Top: the blue and red lines are cables drawn by the user. Bottom: Overview as it appears in the dashboard showing the cable details (i.e. length, radius, bending radius).

3.4.5 Power monitor

A power monitor is displayed on each FLEXRack that is placed in the virtual environment. The power monitor shows details of the individual instruments in that FLEXRack. The power monitor shows a boxplot (min, max, average, and 95% confidence interval) of the instrument power. If the total power of all the instruments exceeds the power which the FLEXHab energy systems can generate, a warning is issued.

4 Discussion & Conclusion

The presented demonstrator provides an innovative training solution that can lower cost and increase flexibility of training and experiment configuration. The demonstrator has the potential to reinvent or complement classical training. Currently training facilities, such as simulators and psychical twins are high in demand and provide less versatile training. It is a challenge to provide trainees with the training time needed, because it is often fully booked with training sessions. This demonstrator enables trainees to familiarize themselves with the facility without needing to actually be there. Elementary aspects of training can be performed remotely enabling precious training time in the real FLEXHab to be spent efficiently and effectively. Additionally, remote training facilities can be used for refresher training or recap.

To create a complete and sophisticated experiment design, the presented demonstrator supports team collaboration in real-time and from remote locations. Insightful discussions can be held without co-location and different tools enhance the discussion with data and new insights. Instructors, experts and peers (e.g. science workforce / expedition planning and experiment execution) are easy to consulate due to the multi-user functionality.

As described earlier, phase 1 addresses Virtual Reality and phase 2 Augmented Reality. The addition of AR will provide interesting new collaboration possibilities. Besides possibilities for new tools (e.g. data streams, procedures) the physical facility and digital twin can be merged, which new abilities to collaborate.

During the development Human-Machine Interaction (HMI) experts were consulted on the visualization of the information in the dashboard and users' aids, as well as the design of the menus. Formal evaluation with HMI experts should be conducted, as well as multi-user tests focused on usability aspects. These tests should verify and validate correct design of and intuitive use of the application.

Finally, once the LUNA analogue facilities have been built and are available, (multi-) user testing during analogue test campaigns are needed to evaluate the complete VR, AR and Mixed Reality training framework developed during this project.

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