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FLEXHAB WORKING MODULE - ARCHITECTURAL REQUIREMENTS AND PROTOTYPING FOR A LUNAR BASE ANALOGUE

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Abstract

Analogues and simulations play an important role in preparation for space exploration. They allow us to test experiments before sending them into space, develop countermeasures for the special conditions, or study human behaviour in similar environments. The so called FLEXhab, Future Lunar Exploration Habitat, will serve as a lunar base analogue in order to create a training and experimental environment at the European Astronaut Center, EAC.

The design of a potential lunar base is very much affected by the specific environmental conditions. Therefore, these are analysed to implement the effects into the analogue, with the goal to create a similar interior and to test countermeasures for specific challenges.

Additionally, the potential tasks carried out inside a lunar base are influencing the habitat design, as well as the analogue and are therefore transferred into possible use-cases for FLEXhab.

This paper presents a design for the interior of the FLEXhab working module, based on a previously developed concept. (O. Punch, T. Dijkshoorn, Spaceship EAC, 2016)

Furthermore, the so called FLEXrack is presented, a recently developed movable rack system. The concept will increase flexibility for exploration module design and increase the available space for tasks and experiments inside the module. To give a first impression of the design and the FLEXrack concept operationally, a prototype is built and evaluated at the EAC. Finally, design requirements for the final design of FLEXhab, the integration of FLEXrack within FLEXhab, as well as for analogues in general are presented.

Keywords: Lunar base analogue, FLEXhab, FLEXrack, Architectural requirements, Prototype

Acronyms/Abbreviations

ISRU: In situ resource utilization
ESA: European Space Agency
EAC: European Astronaut Center
ISS: International Space Station
ISPR: International standard payload rack

1. Introduction

With the vision of the moon village, ESA has clearly set its focus of the next decades on going back to the Moon. [1]. That means that future astronauts must be trained for lunar missions as they are now trained for their missions to the ISS. As the training facility especially for European Astronauts, but also for others training on all European contributions for the ISS, the European Astronaut Center needs to extend its capabilities for the upcoming tasks. [2]

As one first step, the LUNA project was already established and will soon start its construction. A dome with a diameter of 35 m will simulate the lunar surface to train astronauts, as well as to test new technologies. Furthermore, the Spaceship EAC initiative was created in 2012 to focus on many different fields “to investigate innovative technologies and operational concepts in support of ESA’s exploration strategy.”[3].

As one of many projects within Spaceship EAC, the FLEXhab simulation habitat will extend the training capabilities of EAC. It will provide the lunar base from which the lunar surface inside LUNA can be accessed. Additionally, all kinds of tasks can be simulated and tested in the analogue environment, from experiments over design approaches to the control of robots inside LUNA.

Fig. 1. LUNA and FLEXhab working module (Credit: Orla Punch)

In the first phase of the project, the working module will be built. The exterior design has already been developed (by Thomas Dijkshoorn and Orla Punch, Spaceship EAC), resulting in an interior of 3.26 x 10.32 x 2.40 m (LxWxH), divided into three compartments as shown in figure 2. The main goal is to create an analogue facility that provides a flexible interior for different simulations and trainings for ESA as well as external partners at low construction costs with the use of COTS products.

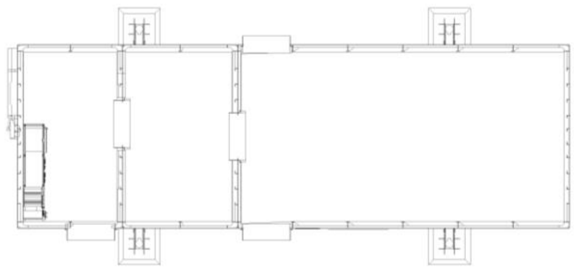

Fig. 2. Floor plan of the module

2. Rational

Looking at existing analogues, it is fair to say, that most of them investigate the effect of isolated confined environments on humans social behaviour and physical effects, while awareness of the impact of the built environment is getting more and more attention.

As a next logical step, not just the impact of a common situation needs to be studied, but also countermeasures for the observed social, psychological and physiological phenomena need to be developed and tested in an analogue. According to the achieved knowledge, improvements in habitat design can further be used for space applications to reduce the upcoming impact of isolation and confinement as well as to simply create a more pleasant and productive environment for future astronauts, especially considering long term missions.

Therefore, the aim of this paper is the design of an adaptable and flexible interior space specifically addressed to the special conditions that would appear on a lunar base. The development of use cases and the evaluation and improvement of design and usability through a prototype will then result in architectural requirements for the lunar base analogue FLEXhab.

3. Analysis

An analysis of the lunar environment, has shown that the design of a lunar habitat is mostly influenced in terms of form and shape. The construction technology will affect the interior of the habitat and therefore cause different constraints.

Regardless of whether materials are sent completely from Earth or build by ISRU technologies, a lunar base will (at least for the near future) always have to deal with limited space, isolation and confinement. Apart from the environmental aspects, the main driving factor is the capability of the launch system.

On Earth the environmental aspects of the Moon have no direct influence on habitat design. That means that the shape of the habitat can be chosen, for example, referring to a specific lunar base concept. Additionally, Earth based requirements such as transportation or location may be the driving factors. Also some of the environmental factors of Earth need to be considered for the analogue as well. In a high fidelity simulation of a lunar base, the sound of rain on the habitat´s roof for example, needs to be avoided.

One of the biggest challenges of the lunar environment is the lighting situation. Appropriate solutions shall be tested to create an Earth like environment inside the volume. Not only because of the limitation of windows in a lunar base, but also due to the different day-night-cycle.

Isolation and confinement can not only cause social tensions within the crew but also physical effects such as myopia due to no possibility of looking into distance [4]. The so called sensory monotony caused by the everyday same small environment [5] may decrease the crew’s performance, which is why countermeasures should be established.

Furthermore, additional requirements apply by the tasks that should be carried out during the simulations. The main purpose of a lunar base, as well as the later designed FLEXhab, is scientific work. As no specific mission scenarios are defined so far, only assumptions can be made on what exact work related tasks the crew of a lunar base would have to carry out, which was done based on the ISS as well as current projects within the Spaceship EAC team.

Due to different levels of gravity the interior design of an analogue adheres to spatial conditions of Earth. Nevertheless, especially the aspect of maintainability of the habitat adds additional constraints to the overall interior design. Solutions to meet the technical requirements as well as a pleasant interior environment need to be developed.

Apart from the lunar conditions and lunar base activities, existing analogues served as an important reference, for example the Mars 500 simulation. One of its participants, Romain Charles provided important insights and input through informal talks.

4. The FLEXrack concept

To create a changeable interior environment and allow for adaptions between different simulations as well as different training methods throughout the lifetime of FLEXhab, the concept of FLEXrack was developed.
A rack system basically provides a modular layout of components, such as experiments, furniture, or storage,

to allow exchangeability as well as replaceability of those modules. Taking the ISS as an example, an ISPR can be placed on floor, walls, and ceiling due to microgravity. Furthermore, new experiments can replace old ones by exchanging the racks as a whole, or in part, due to the standardised dimensions and infrastructure. Different arrangements are possible during the lifetime of the space station, which was not only necessary due to the modular assembling over several years, but also due to the previously unknown experiments that are now placed there. [6]

Microgravity in that case has a big advantage. The racks on the ISS, such as the European drawer rack are quite bulky (1046x850x1836mm) and heavy (about 500 kg at launch) without that being a problem. [7] [8]
On Earth at least a similar, if not even higher level of flexibility is required, due to the unknown upcoming tasks as well as the possibility of cooperation with other agencies or industry as well as different types of trainings. Therefore, a rack system was developed, adapted to Earth's conditions and FLEXhab requirements. All this should be achieved by a sliding system, in which the racks are integrated. Racks can then not only be rearranged by replacing them, but also for different mission scenarios or even different activities. Racks currently not in use should be moved to the side to open up space for things that need to be accessible. Comparable to storage systems in libraries or archives where corridors are only opened up when needed. Supported by folding mechanisms to create different situations, the use of the interior space of the habitat will be as efficient as possible, while sustaining a high level of flexibility.

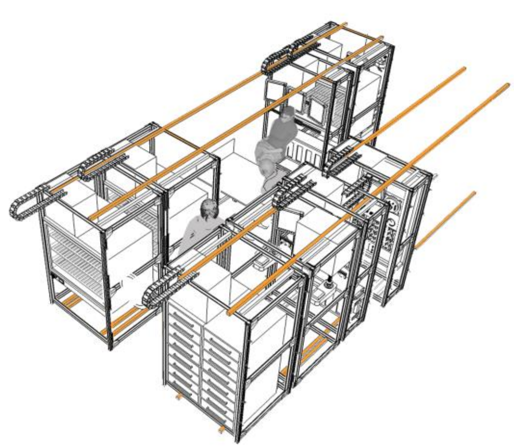

Fig. 3. FLEXrack concept (Credit: Orla Punch)

5. Interior Design

The interior design of the working module basically addresses to three main issues of a lunar base:

1. Isolation and Confinement
2. Missing/Different natural light
3. Changing spatial requirements

Those result in three main design measures:

1. Visual extension of the interior space
2. Simulation of natural light
3. Changeable interior

Apart from the overall layout, location and size of racks as well as technical necessities which have been implemented, those main design elements will now be illustrated showing the main compartment.

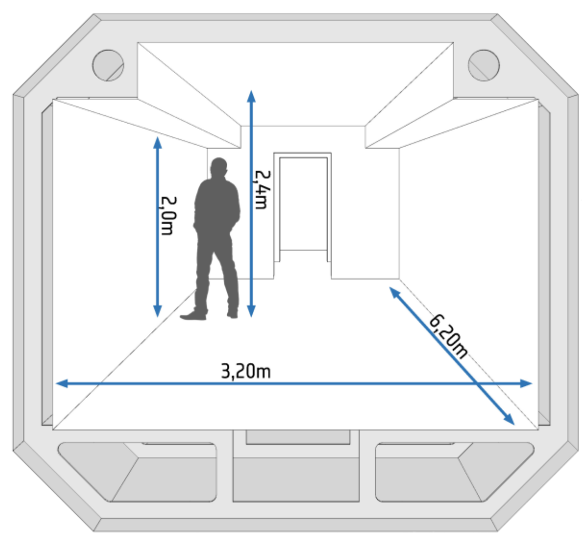

Fig. 4. Main compartment, dimensions

For easy maintainability, removable panels are used for surface covering, adding a strong visual element influenced by size and format. Further, the later introduced FLEXrack requires rails for movement which adds another visual element. Additionally, the bottom and top corners are used for cable management, creating a more accommodating side area within the module due to its specific shape which is caused by construction and subsystems.

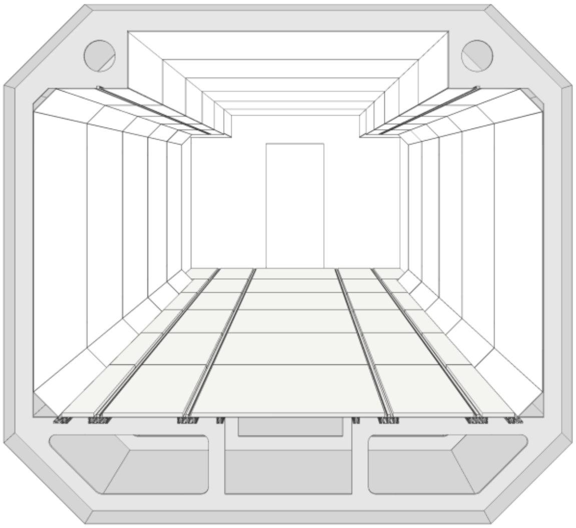

Fig. 5. Application of boards and rails

Illumination is added on the ceiling through indirect lighting, to increase the perceived height of the module. Basically the same effect is used also on the walls, introducing a partial setback, or window reveal layer on the outer walls for several reasons. The indirect lighting through backlit translucent acrylic glass also increases the perceived interior width. Furthermore, the so created secondary layer allows for integration of additional rails that are needed for FLEXrack. Additionally, the so created lighting best simulates the usual lighting situation in conventional buildings with light coming from the side.

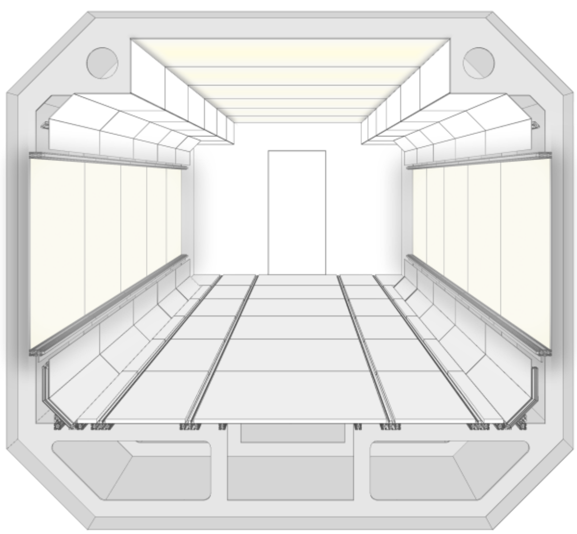

Fig. 6. Application of lighting

To avoid visual monotony as well as to allow for individualization and simulation of different environments, the lighting shall be capable to create different colour temperatures in order to natural light. This could even be pushed further by background images within the window reveal layer and the ceiling to even create either simulated earth environment, or the other way round, to create a lunar environment for simulations.

Apart from lighting, also the use of colours and materials changes the perception of an interior space. In relation to colour schemes developed and investigated by Maria Durao light pastel colours with similar chromatic value should be used for the interior in first place, "*as they allow for the interior space to expand visually*." [9]

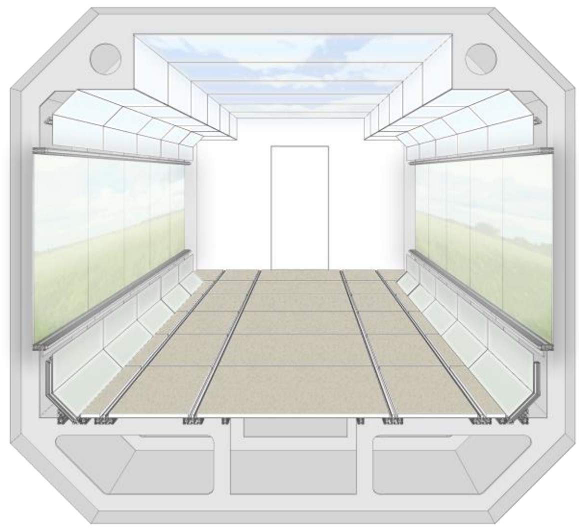

Fig. 7. Colour scheme and simulation of environment

Also, the interior space is not just perceived visually, but also by listening, touching, and even smelling. Materials provide an additional design element within the habitat. Limitations in payload capacities as well as safety issues limit their variety in current space habitats. Restrictions according to outgassing and flammability, as well as weight, make the use of wood for example almost impossible. [10]

Nevertheless, the positive effect of different materials is indisputable. Especially, in isolated, confined environments, the goal is to get as close as possible to a natural environment. As an example, at the Halley VI station in Antarctica, cedar panels are used as they *"give off a pleasant smell in a place where there are no plants"* [11]. The haptic properties as well as the texture, or even smell of materials can help reducing the effects of isolation.

The Mars 500 habitat was almost entirely using wood for panels and surfaces, as well as furniture. Feedback on the habitat design according to the use of material was generally positive. The wooden floor and wall panels allowed the crew to sit and lean onto, which would have not been as comfortable with metal, for example. [12]

For the overall interior of FLEXhab, similar to the application of colours, a discrete approach is chosen, as more specific elements shall be added according to specific tasks and within specific racks. Certain areas could be equipped with materials according to their functions to study and evaluate their effects.

The window reveal layer can as well be used for the application of different materials, allowing for individualization or adaption to specific needs, e.g. the improvement of acoustic insulation through the application of acoustic textiles.

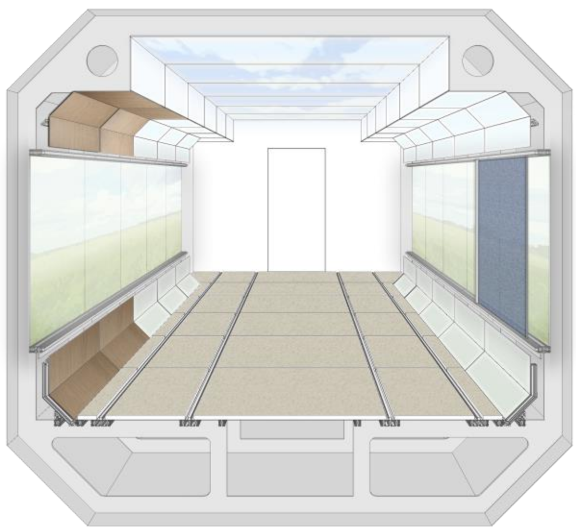

Fig. 8. Possibility apply different materials

6. FLEXrack 2.0

The intention of FLEXrack is to achieve a maximum amount of Flexibility through moveable racks, as well as efficient use of space through rearrangement and rack design.

The racks are designed according to the previously described interior, basically following the same design principles, resulting in the overall design shown in Appendix A. Apart from that, several parameters, such as dimensions and layout of translation areas, have been defined. A certain amount of flexibility is also ensured for rack design, allowing adaptions to specific experiments or upcoming requirements, while keeping a pleasant overall interior.

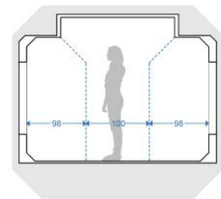

Fig. 9. Definition of dimensions for racks

As the main advantage of FLEXrack, specific attention is given to the aspect of reconfiguration. Several possible scenarios have been developed based on current projects within the Spaceship EAC team as well as input from experts. Those have been especially compared regarding the frequency of changes:

1. Rare changes throughout the lifetime of the habitat
2. Mid-term changes in between different simulations/trainings
3. Short term changes during simulations/trainings

Theoretical comparison of those has shown that a higher frequency of changes adds an extra amount of complexity in planning. For example, when arranging racks, it even has to be considered where tools for one experiment are stored, otherwise they might be blocked by other racks when needed. Frequent changes on the other hand allow for more efficient equipment of the habitat. Additionally, the possibility to change the interior space adds opportunities for the crew as well as more equipment within the same space if well planned. Figure 10 shows different arrangement of workstation with the same configuration of racks.

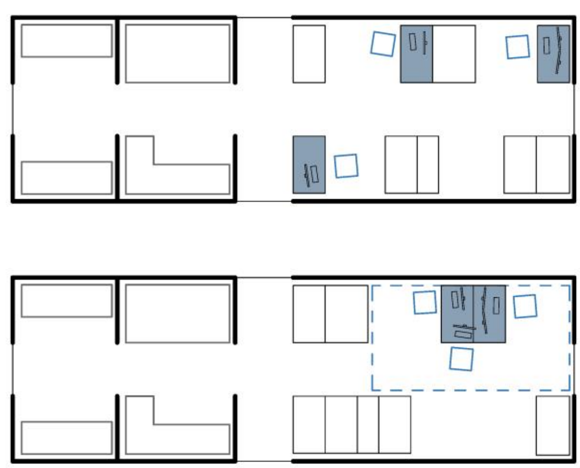

Fig. 10. Spatial configuration supporting or impeding interaction

7. Prototype

The previously described interior design, as well as the FLEXrack concept, are transformed into a prototype located in a foreseen space within the Agora office at the EAC. Considered to be a small part of FLEXhab it allows for evaluation and adjustment of the general design approach and further serve as a real size model to visualize and evaluate the FLEXrack concept.

The spatial requirements for certain activities previously related to literature and experience can be tested and evaluated. Apart from that the prototype serves as an important tool to get input and feedback from project related experts for further improvement of the final design.

Considering a similar construction approach for the real habitat, the prototype also allows for identification of improvements in construction and cost driving factors.

Constraints

For the construction of the prototype priority was given to ease of assembly and also exchangeability. It is fully constructed out of COTS products to ensure easy replacement of all elements as well as keeping connections, fixations and joints not just simple but also within one overall system. A modular system of aluminium profiles, produced by company called Item, allows for easy adaptations and changes as well as extensions due to the vast amount of possible solutions the system offers. [13]

For the above described reasons, some differences exist between the prototype and the FLEXhab design: The prototype is constructed in a conventional open office space. This means, the space is not a closed volume with limited dimensions. Its location is a niche with dimensions of approximately 2.6 m in width and 2.7 m in height. Even though, the prototype itself has the same spatial dimensions as FLEXhab, it is perceived differently due its surroundings.

The railing system is a key element of the FLEXrack concept and therefore requires special attention for two main reasons: firstly, its usability is essential for the whole concept and secondly its presence will affect the interior space of the module. Easy movement needs to be provided, otherwise the advantage of quick effortless rearrangement is gone. A manually operated rail system was chosen in the prototype for simplicity and ease of assembly, whilst the rail system used in the actual FLEXhab will be automated. That results in the need of manual fixation and release before and after movement of the racks in the prototype.

Setup

The prototype will be equipped with three racks, which serve as technology demonstration, but are also adjusted to the needs of the office space.

For that reason, the setup is focusing on a basic workstation, thus providing space for at least one person working, for example with a laptop sitting and standing. Additional screens allow the workstation to become a control station for rovers. Two additional racks, serve as shelves but can also be seen as racks for experiments. The design of those racks implements an empty space at the height of the table to allow for horizontal stacking of the racks.

Scenarios

Through reconfiguration of racks a variety of scenarios can be achieved. Both, design and usability of the prototype, are evaluated by those developed scenarios, such as the use of the workstation or maintenance activities, as well as through individual use by the author and additional test subjects.

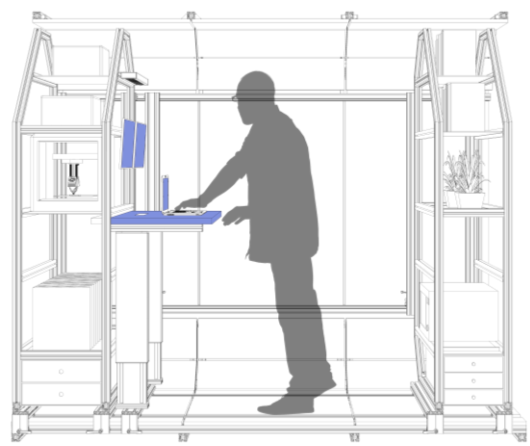

Fig. 11. Example of prototype scenario

Through feedback, observation and personal experiences, a résumé was drawn for the prototype concerning the overall construction, maintenance scenarios, movability of racks, available space, use of the workstation and lighting.

Fig. 12 & 13. Evaluation of developed scenarios.

8. Lessons learned

Based on the previous evaluation as well as the overall design development, requirements for the final design of FLEXhab have been defined. As certain parameters have been considered as variable through the final design phase, the requirements allow for adaption and application to changes, which makes them also applicable to other analogue facilities. On overview of some main elements is given in the following.

For the overall design of FLEXhab, the relation of interior and exterior dimensions are considered as especially relevant as they refer to either limitations in transportation or interior space. Priority needs to be given to one or the other.
In addition to the interior design presented in section three and Appendix A, design guidelines applicable to changing parameters through the final design phase have been defined, such as the example illustrated in figure 14.

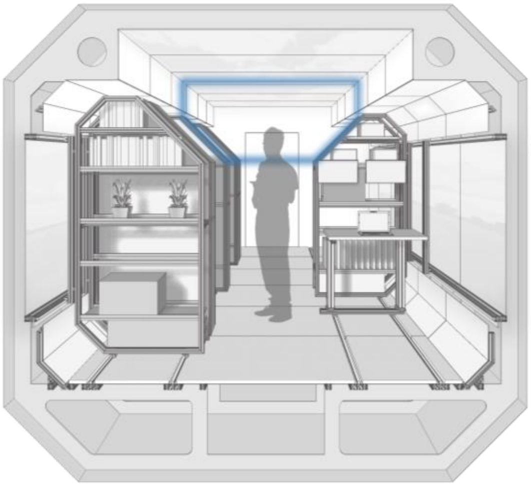

Fig. 14. Design guideline for the interior: maximize available volume at eye-level to increase perceived space

In terms of available space, the evaluation has shown that required space varies between individuals as well as duration of activities, which generally supports the concept of reconfiguration.

FLEXrack 2.0 proved to be not just beneficial for the creation of different interior spaces in theory, the movability of racks already made assembly of the prototype easier and additionally facilitated maintenance activities. A lot of potential lies in the design of the racks in terms of multiple use and additional sliding and folding mechanisms to even increase the efficient use of space. Horizontal surfaces such as workstations, for example, occupy a lot of space which can be used for other things when they are not needed. The horizontal layer for stacking applied in the prototype is only one possibility to do so.

Construction of the prototype needs improvement before application in the actual habitat, nevertheless the use of COTS products generally worked well. Some specific solutions need to be developed for more advanced and critical elements such as the rails.

Even though, evaluation of the lighting situation was limited in the prototype, requirements exceeding the legal ones have been defined as well as solutions to allow for changes between artificial and natural lighting.

In terms of materials, the prototype is meant to be used for further evaluation. As an example, the workstation was equipped with a wooden surface, while the rest of the prototype appears quite sterile, similar to the current situation on the ISS, to visualize the difference.

Fig. 15. Prototype in use

8. Conclusion

The evaluation of the lunar environment and lunar base activities have shown that the most relevant aspects in simulating a lunar base are isolation and confinement. Living in an isolated artificial environment requires countermeasures to create not just a comfortable environment, but is also critical for mission success. Similar effects would also appear for example on Mars, therefore those are applicable for analogues in general.

Apart from the spatial requirements given by the activities, the design measures presented in this thesis are focusing on three main elements:

1. Lighting – To allow for natural Earth-like conditions
2. Colour and Materials – to avoid visual monotony as well as to increase comfort contrary to current sterile space habitats.
3. FLEXrack – to increase flexibility and efficient use of the limited space and allow for adaptions, as well for sensory stimulation.

The prototype allowed for evaluation and improvement of the spatial and technical requirements. Together with the developed scenarios for FLEXrack, specifically a conclusion for the integration of FLEXrack is presented in the following.

FLEXrack

Based on the suggested design as well as the defined requirements, the use of FLEXrack can add significant potential to the FLEXhab analogue. Nevertheless, conditions and design other than the ones described, might reduce those advantages.

The biggest concerns are on the one hand operational aspects, meaning that FLEXhab will be used in a different way than what FLEXrack is supporting. On the other hand, usability must be ensured. The introduction of FLEXrack must not limit the user in any case compared to a non FLEXrack solution, which is mostly depending on technical aspects.

The required flexibility of the interior is not just seen as a necessity for the unknown tasks or different training techniques that will be carried out in the habitat. The integration of a movable rack system adds potential value: the analogue can be used for simulations with different spatial configurations. Different cases can even be tested and evaluated to investigate the concept's benefit for future space habitats.

As the goal is also to develop new training methods, FLEXhab allows not just for training specific tasks, but more creates an overall simulation of a lunar base environment.

Additionally, studying the effects of different design measures will not only increase habitability of future space habitats, but will also lead to spin-off for terrestrial applications. The fact that colours, materials, and light have a big influence on human beings is a well-known fact everyone can experience on their own. Nevertheless, those positive effects are hardly measurable. In a closed environment, those are likely even more intense, which will result in more significant results.

One major issue encountered during the design process was the combination of flexibility and efficiency. Those two interfere with each other for the following reason:

The most flexible interior is probably an empty room as it can be equipped with whatever is needed at the moment. Furthermore, rearrangement is easy.

The most efficient space is planned into every detail, adapted to specific needs.

Combining both of those approaches, creates the danger of one reducing the other. With the design of the FLEXrack system a solution is presented, which combines the strengths of both, by easy reconfiguration that allows for multiple use of space.

One of the biggest disadvantages of the concept is the fact that some racks are not accessible permanently. Precise planning needs to be done in order to avoid situations, where things in need cannot be accessed. Spontaneous changes between activities might be prevented by the current configuration of racks. Looking for an experiment that is stored will not happen casually, which was mentioned as a concern by members of the EAC team. Furthermore, warnings and signs in case of failure need to be located on a place that is always visible.

The limitation of access is defined by the amount of racks in the habitat. Therefore, different scenarios can also be tested to improve the concept and adapt to people's needs.

Besides those disadvantages, the crew of simulations gets the possibility to create different interior arrangements according to their preferences. Additionally, the space gained through the concept serves the crew. Especially for long duration simulations, the additional space can be used to add comfort, which would be impossible in a conventional layout. FLEXrack can therefore also be seen as a tool for future astronauts to create and design their own physical environment. A lot of potential lies in the design of the racks, by the implementation of sliding and folding mechanisms as well as through combination of different rack forms.

For astronaut training reconfiguration allows for more available space in case of demonstration for several people while everything else (experiments, workstations, etc.) can stay in FLEXhab.

Supplementary to all the movable parts, within the whole habitat also some stationary parts are required. Even though, FLEXrack shall only be implemented in the main compartment, meaning the other two serve as a steady environment, it will still be beneficial to have some stationary parts in there as well.

A final prove of concept can only be achieved by several real simulations. However, FLEXrack is designed to not just allow moving racks, but also enables easy replacement of racks like a static rack system.

Even without frequent rearrangement, a positive effect is achieved. As of now, astronauts living in unpleasant spatial conditions have no chance of improving their situation. An adjustable environment would increase crew comfort significantly. The private compartments in the Mars 500 mission, for instance, did not provide sufficient acoustic separation [12]. Even though it was not the case often, the medical compartment could be used for more privacy or better acoustic insulation due to its location. Simply having the possibility to change an unpleasant situation adds additional comfort for each individual, even though it is not used often.

Overall, FLEXhab, including FLEXrack, allows

- easy and quick reconfiguration within short time
- increased amount of racks compared to static solution
- flexibility in rack design
- evaluation of reconfigurable space for future space habitats
- testing the effects of design and especially the changing environment on crew's performance
- functional and visual reconfiguration

but requires

- precise planning in advance
- defined spatial requirements of racks
- higher technical effort
- more expensive construction than static racks
- a suitable operational structure.

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Appendix A – Interior Design FLEXhab working module

Fig. A.1. Section of the FLEXhab working module. Simulation of natural environment as countermeasure.

Fig. A.2. Section of the FLEXhab working module. Simulation of the lunar environment to study its effects.

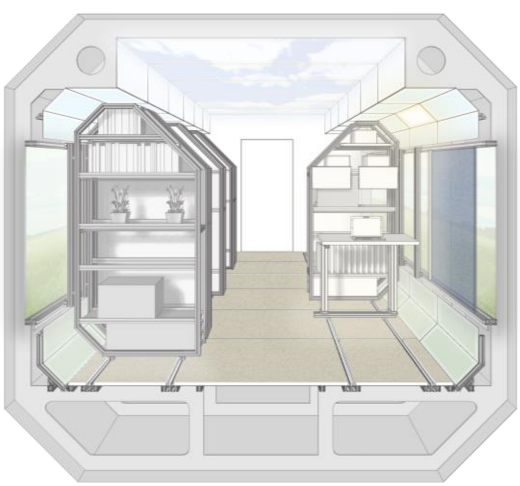

Fig. A.3. Section showing the design measures explained in section four complemented with FLEXrack.

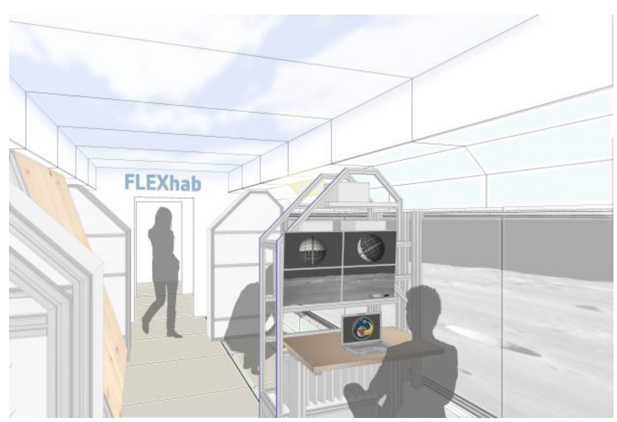

Fig. A.4. Vision of the interior space while simulating the lunar environment.

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