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Designing for maximum adaptability before, during and after spaceflight

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Abstract

Possible psychological complications of a long space flight beyond the Earth low orbit have been under discussion since such missions were first proposed. Those complications are related to the confined environment of a spacecraft during the flight and habitats on the moon or Mars surface, crewmembers' personalities, cultural and social differences, and work-related stressors. As a result of crew exposure to all or some of these difficulties, crewmembers may not be able to perform at their best capacity and fulfill their mission requirements.

This exploratory paper examines architectural and design strategies that address and potentially alleviate stressors through stimulating crew adaptability to new environments and circumstances. These strategies are analyzed based on following dimensions for adaptive performance:

- Self-controlled behavior in emergencies and crisis situations.
- Managing work-related stress, especially in critical situations.
- Innovative approach to problem solving.
- Maintaining productive operations in unpredictable and unknown situations.
- Continuing learning and applying new technologies and procedures.
- Facilitating social and cultural adaptability.
- Displaying adaptability to physical environment and managing it to fit the purpose.

The paper aims to analyze these listed dimensions through relevant case studies and to identify any potential opportunities for the development and integration of supportive design strategies to increase adaptability in crewmembers. In a summary, a platform for further inquiry into architectural and design strategies is proposed for more in-depth discussion in the future.
Keywords: space architecture, habitability, mission planning, design, spaceflight, adaptability.

Acronyms/Abbreviations

Space Launch System (SLS), In-Situ Resource Utilization (ISRU), International Space Station (ISS), Space Architecture Technical Committee (SATC), European Space Agency (ESA), Russian Federation Space Agency (RFSA), National Centre for Space Studies (Centre National d'Études Spatiales, CNES), German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt, DLR), Japanese Aerospace Exploration Agency (JAXA), China National Space Administration (CNSA), Institute of BioMedical Problems (IBMP), Astronaut Center of China (ACC).

1. Introduction

There are numerous analogues and mock-ups associated with the various space agencies and their respective facilities. These however, lack a true holistic integration in order to better provide a greater role in design and the increase in adaptability that design can play in future missions.

2. Overview of Current Design Strategies

Up to date design strategies for space exploration missions applied by international agencies focus on fulfilling in-flight mission goals while providing appropriate safety and comfort for the crew. That includes pre-flight training and post-flight adaptation periods. Shifting the design focus more towards human

Types of space analogues:

1. Airtight/pressurized structures
2. 0-G testing/parabolic flights
3. Underwater facilities
4. Isolation chambers
5. Remote locations
6. High altitude training
7. Hyperbolic and centrifuge chambers

Analogue and training facilities for human spaceflight testing and training by agency include:

USA-NASA

1. Human Exploration Research Analog (HERA) (JSC)
2. NASA Space Radiation Lab (NSRL)
3. Human Exploration Spacecraft Testbed for Integration and Advancement (HESTIA) (JSC)

4. Aquarius; NASA Extreme Environment Mission Operations (NEEMO)
5. Neutral Buoyancy Laboratory (NBL pool)
6. Desert Research and Technology Studies (Desert RATS)
7. In-Situ Resource Utilization (ISRU) (NASA, Pacific International Space Center for Exploration Systems and the Canadian Space Agency)
8. 0-G parabolic flight (Novespace, CNES, ESA)
9. Antarctic Stations - National Science Foundation (NSF)
10. Human-Rated Altitude Chamber Complex (ACC) (JSC)

Russian Federation Space Agency (RFSA, Roscosmos)

1. Ground-based Experimental Complex (IBMP)
2. Underwater (Gagarin Cosmonaut training center)
3. Centrifuge (Gagarin Cosmonaut training center)
4. 0-G parabolic flight (Gagarin Cosmonaut training center)
5. Survival camp

European Space Agency (ESA)

1. envihab (DLR)
2. 0-G parabolic flight (Novespace, CNES)
3. Concordia (French Polar Institute, Italian Antarctic Program)

Canadian Space Agency (CSA)

1. Pavilion Lake Research Project (PLRP)
2. Haughton Mars Project (HMP)

China National Space Administration (CNSA) [1]

1. Centrifuge (ACC, Beijing Space City)
2. Hyperbaric chambers (ACC, Beijing Space City)
3. 0-G parabolic flight (Gagarin Cosmonaut training centre, Roscosmos)
4. Underwater facility (ACC, Beijing Space City)
5. Space module full-scale training simulator (ACC, Beijing Space City)

JAXA researchers participate in analogue studies through NASA and astronauts conduct their training in the USA, Russian Federation and Europe.

Existing analogues that are used for conducting human spaceflight research, present certain limitations and shortcomings. The most common amongst them is the lack of airtight conditions for systems and habitable environment testing. Others include associated to remoteness psychological complications and limitations in duration of conducting crew operational testing. In the Table 1 some of the existing analogues are compared in relation to presence or absence of these conditions.

Table 1. Selected analogue facilities and their comparison based on conditions.

Analogues		Airtight	Long-term	Remote
HiSEAS		NO Human research related to isolation, confined and remote conditions, surface geological study simulations.	YES 4 to 12-months missions.	YES Mauna Loa side of the saddle area on the Big Island of Hawaii at approximately 8200 feet (2,500 m) above sea level. The crew is isolated for duration of the study.
NEEMO		YES A pressurized module is located 62 feet (19 m) below the ocean's surface provides living similar to in a spacecraft and to test spacewalk techniques.	NO A typical NEEMO mission lasts from 7 to 14 days.	YES The Aquarius research facility is a residential laboratory that located off the coast of Florida. Aquanauts spent one or two weeks in partial isolation.
HESTIA		YES The facility supports research on element, sub-system, and system level non-human and human activities at sea-level and under reduced pressure conditions.	NO Up to 90 days isolation missions with re-supply options.	NO The structure is located in Building 7 at NASA Johnson Space Center (JSC). Although the location isn't remote, the crew is isolated for the length of the study with scheduled re-supply events.

MARS500		NO Research of crew performance and dynamics in confined environment and associated with it physiological stressors.	YES 520 days isolation mission (Mars mission simulation).	NO Located in the Institute of Biomedical Problems (IMBP) in Moscow, Russia. The crew was partially isolated for the length of the study with scheduled re-supply events.
MDRS		NO Research on human factors in confined and isolated environment and field studies simulations.	YES Up to 8-months missions	YES Located in the desert of Utah, USA. The crew is partially isolated for the length of the study, monitored and receives regular resupplies.
HERA		NO Research of human factors under isolation, confinement and remote conditions.	NO Planned mission durations may range from 7 days up to 45 days.	NO The structure is located in Building 220 at NASA Johnson Space Center (JSC). Although the location is not remote, the crew is isolated for the length of the study with scheduled re-supply events.

2.1 Associated training

Astronaut and cosmonaut training includes exposure to 0-G conditions during parabolic flights, underwater training for EVA task performance, survival training for after-landing preparedness, exercising and medical evaluations. Table 2 compares three conditions that astronauts experience during pre-flight training by the agency.

Table 2. Astronaut training aspects and conditions by the agency.

TYPE	NASA	ESA	RFSA	CNSA*
0G (physical)	N	Y	Y	Y
0G (psychological)	N	N	N	N
Confined (physical)	Y	Y	Y	Y
Confined (psychological)	Y	Y	Y	Y
Remote sites (psychological)	Y	Y	Y	Y

NASA and ESA are exploring augmented and virtual reality tools as means for advancing astronaut training. Several recent developments in that area have proved that VR can be added to the common list of astronaut training routine [2].

NASA has started using its mixed reality astronaut training recently. Along with a commercial partner, the agency created a mixed reality International Space Station simulator that can be used for educational and training purposes.

New 3D Visual Training (3DViT) has been recently introduced for operations on-board of the International Space Station [3]. The 3DViT tool prototype was successfully used by NASA and ESA astronauts during two ISS missions. These technology demonstrations proved usefulness of 3D visualization methods for on-board training. They can also be considered as an addition or substitute for some pre-flight ground training procedures [3].

RFSA (Roscosmos) expanded and advanced Cosmonaut training procedures with emphasis on advancement of scientific research capabilities on board of the ISS. They are task-oriented simulators including computer-aided mockups of space experiments and scientific tools based on interactive 3D models of Russian segment scientific equipment [4].

2.2 Existing Problems and Possible Deficiencies

In general, the most common reasons for human error occurrences include [5]:

- Fatigue, stress, injuries or illness;
- Degradation of acquired skills and knowledge;
- Insufficient training (including the lack of professional training for unforeseen operations and off-nominal situations);

* Based on open and publicly available sources.

- Insufficient understanding of an operational situation.

Since 70 to 80 percent of accidents during a mission are due to human factors errors, current strategies adopted by space agencies and used for the ISS crew training suggests minimal crew autonomy during the space mission and assumes permanent ground support during the flight [5].

Even though such an approach can be effective for orbital missions, it may not be sufficient for long-term and deep space missions with a diverse and sizable crew. Expansion of space activities in the future will call for crews that consist of professionals with diverse backgrounds, age groups, and cultures. Other complications can be related to the specifics of commercial activities, companies' status quo, and security protocols.

Current agencies have defined sets of pre-flight and post-flight procedures and trainings (Table 3).

Table 3. Before, during and after space flight training by the agency.

Agencies	Before	During	After
NASA	Under-water/ simulators/ cross agencies	Applying on-fly, 3DViT training	Medical check, adaptation
RFSA	Survival/ under-water/ simulators/ cross agencies	Adjustin g and applying in-flight	Medical check, adaptation
ESA	Under-water/ simulators/ cross agencies	Applying on-fly, 3DViT training	Medical check, adaptation
CNSA*	In-house training with 0-G parabolic flight at CTC RFSA	Applying in-flight	Medical check, adaptation

2.3 Summary of shortcomings

- Cross-analogue/mock-up fidelity evaluation by returned-from-space astronauts is missing.
- Lack of an integrated process of evaluation and correction for all types of analogues and training facilities
- Uniformity of participant characteristics (merits, training, age, behaviour)
- Time gaps between mission ground training and on-board task performance
- Existing VR training programs are task-oriented and do not address integrated problem solving

3. Strategic design implementation

The inherently claustrophobic and stressful nature of confined spaces implies that the restorative effects of virtually manipulating the environment and altering how the environment is perceived could be significant, even if such experience is provided artificially.

We propose an implementation of AR and VR technologies at three levels: 1) personal virtual experiences, 2) human scale projections, and 3) shared social environments. These levels do not necessarily build on each other and are not mutually exclusive.

1) Personal virtual experiences

These experiences are typically provided using head-mounted displays and allow users to be immersed in and interact with artificially created environments. In the context of this paper, we propose the use of VR as an "affective" or "mood inducting" medium: a medium able to elicit different emotions through the interaction with its contents [6]. In fact, the sense of presence in VR is not only linked to the graphic realism provided by the technology, but also to the emotional characteristics of the experience. For example, virtual environments can be designed to induce a specific, emotional response in the user such as joy or serenity. Some of these experiences have been successfully designed to improve and promote the psychological wellbeing of crew members [7]. The incorporation of fractal structures found within the natural environment and incorporated within habitat interior design is also suggested to operate as a successful countermeasure to isolation and confinement stressors [8]. Figure 1 illustrates the implementation of a personal virtual experience using both projection and VR technology. This strategy would be an ideal vehicle to test the viability of fractal structures within the habitable environment.

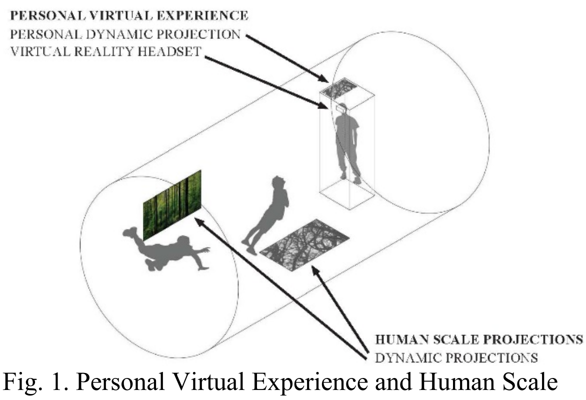

Fig. 1. Personal Virtual Experience and Human Scale Projections Diagram.

2) Human scale projections

In this level, we include personalized projection-based experiences in the private spaces of the crew members and subtle, unobtrusive projections on common areas to enhance the architecture of the spacecraft and/or living environment. Figures 1 and 2 illustrate the concept of human scale experiences, showing projected, or displayed content. Again, this could be a suitable method of testing and researching the use of fractal geometry in a habitat as a means of reducing stress levels amongst crew members.

Experiences in private spaces can be triggered automatically and delivered per individual using persuasive computing to induce or promote specific emotions. For example, the lighting conditions or projected wall fractal patterns of an individual's private living space could be automatically adjusted based on his/her mood (which could be determined by recognizing facial expressions or certain stress patterns) to alleviate stress or encourage relaxation. Similarly, dynamic projections on certain common areas could be used to change the perception of the living space (e.g., by giving walls a "virtual depth" to make them look deeper than they actually are, or by creating virtual windows and skylights that can provide feelings of openness, warmth, and comfort [9]).

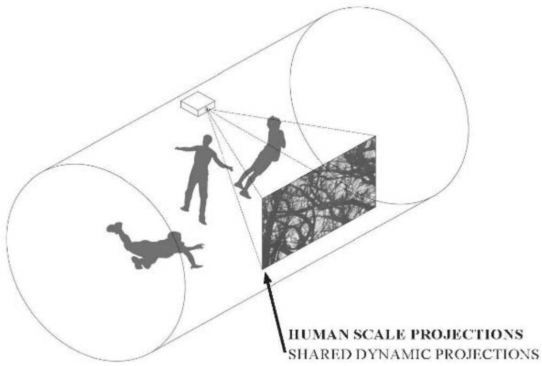

Fig. 2. Human Scale Projections Diagram illustrating Shared Dynamic Projections with fractal content.

3) Shared social environments

This level of implementation involves computer-mediated social experiences in virtual and augmented reality environments to enhance autonomy and reduce feelings of loneliness and isolation. We include Collaborative Virtual Environments (CVE's) designed to encourage active participation, communication, and interaction among crew members, as well as those mediated by virtual agents, avatars, and artificial intelligence systems. Such environments aim to enhance team building behaviour while offering certain level of adaptability to different social and cultural circumstances.

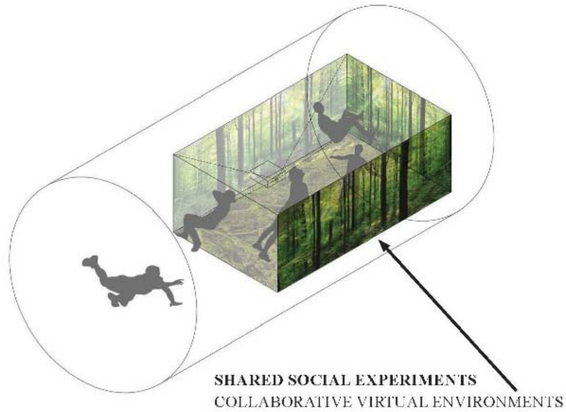

Fig. 3. Shared Social Experiments Diagram illustrating Collaborative Virtual Environments (CVEs), with a focus on interaction and team building.

Research by Wise and Taylor into the use of fractal structures in a work environment suggest an increase of worker performance [10]. Such bionomic design elements can be implemented using effective technological strategies such as the CVEs as illustrated in Figures 3 and 4, where increased crew performance is a desired outcome and could benefit from testing and research to substantiate its viability within future missions. Figure 3 demonstrates recreation of environment for social recreation, figure 4 refers to simulation of future exploration zones for stimulating team behaviour and actions during surface operations.

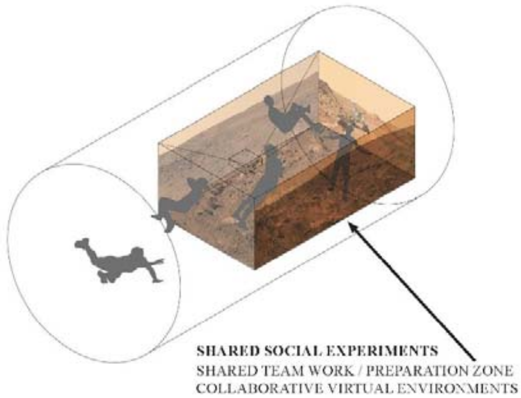

Fig. 4. Shared Social Experiments Diagram illustrating CVEs, with a focus on adaptability and productivity.

3.1. Methodology and design strategy

The proposed methodology for the integration of the proposed design implementation strategies follows a progressive rollout (see Figure 5). The initial research is to be conducted using a combination of off-the-shelf hardware and software to minimise initial expenditure. Once the feedback and results determine that the design strategy is viable, the second stage will involve integration of the necessary technologies into the habitable environments. These environments will include terrestrial analogues and the next generation of space stations and spacecraft supporting extended habitation.

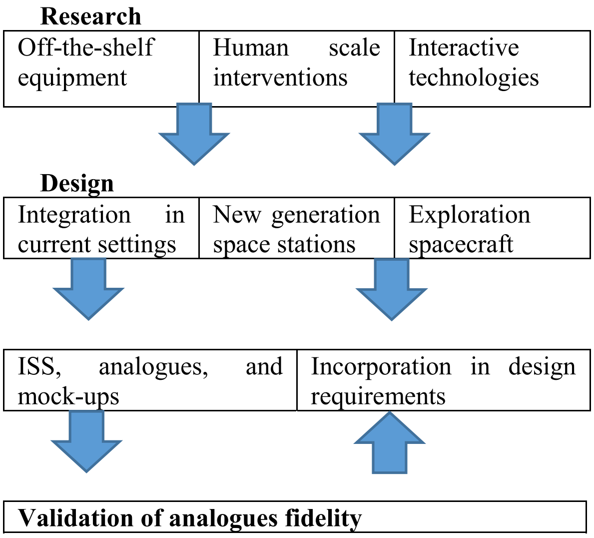

Fig. 5. Methodology and design strategy diagram.

Immediate outcome of the proposed methodology includes development of analogue validation system and strategic implementation of AR and VR design interventions in new generation of space habitats and other facilities. Off-the-shelf equipment in the form of commercial virtual reality headsets can be used to produce personal virtual experiences and with some development, shared social environments including CVE's. Short-throw projectors can be used to create human scale projections. These are technologies that utilise existing hardware and create minimal impact, allowing for changes and alterations in content with little difficulty and without the inflexibility of physical interventions.

4. Projected outcome and discussion of future opportunities

4.1. Adaptive Performance Criteria

Development of criteria for evaluation of adaptive performance strategies is a fundamental step for designing structures for long-term space missions.

Applying VR technologies in diverse analogue facilities will provide information for design decisions to be made not only in regard of interior spaces but of the architecture of the whole spacecraft. That includes: location of viewports that provide visual contact with the vehicle and its surroundings during different stages of a long space mission; training for conducting experiments on board inside and outside of the spacecraft; adaptation for environmental challenges in flight and on a planetary surface.

The integration of augmented and virtual reality technologies also provides the capability for crew adaptability in transit. Familiarity with other crew members can be developed as well as familiarity with the destination.

Figures of Merit (FOM) aspects of adaptability include crew feedback in regard to:

- Training for upcoming operations: using VR technologies for adapting to surface operations inside and outside of the habitat during 0-G conditions of a spaceflight to Mars; and during Mars mission for the flight back to Earth.
- Preparation for unfamiliar environment (interior and exterior): environmental conditions include light characteristics, gravity related adjustments, dust mitigation procedures etc.
- Familiarizing with new settings (internal and external): different layout complications, crew and systems operations and functions, including surface elements and infrastructure.
- Team building during proposed Concepts of Operations (ConOps) for unfamiliar environment and situations: providing stimulating environment for group and team-oriented activities during surface operations and in in-door living and working routines.

4.2. Design Validation Criteria

Design validation of the habitat interior environment with proposed AR and VR three-level technology integration includes three major data collection types: unobtrusive means for collecting data on individual responses to surrounding interior design, direct scientific data collection, and individual and group feedback. FOM aspects for validation of design effecting crew's living and working performance include:

- Perception of distance/perspective
- Perception of lighting (direct and ambient)
- Mission-related task performance over time (increasing, decreasing, changing in parabolic progression)
- Social behaviour over time (individual and group)
- Man-machine/system/habitat interactions

4.3 Criteria compilation and discussion

Combination of results of two sets of FOM provide guidance for design alterations and additions, development of new AR and VR technologies, inflight and surface operational preparedness. They also inform crewmembers from diverse disciplinary, social and cultural backgrounds about mission conditions and their options for design and operational interventions. That will enhance crew's confidence during increased autonomy of a long-term spaceflight.

5. Conclusion

Fundamental to the concern for adaptability before, during, and after spaceflight is the development of a discussion surrounding a holistic methodology to better engage analogues and mockups in the refining of future space stations and spacecraft. This paper seeks to open up this discussion in the hope of producing an improved, and more productive model.

The use of augmented and virtual technologies within the outlined strategic designs provides a clear pathway to exploring the potential of such an integrated methodology. This AR and VR technology also requires minimal physical impact and allows for future updates and content, maximizing its lifespan and research potential.

A discourse concerning agency-wide integration of analogues and mockups that sees astronauts engage with and provide feedback pertaining to their fidelity before and after spaceflight is sought. This can result in a framework capable of producing better designed space architecture, along with the capability to better define necessary design standards, whilst providing more accurate analogues to assist in adaptability.

References

[1] China Space Report, "News and analysis on China's space program," 14 June 2017. [Online]. Available: https://chinaspacereport.com/programmes/astronaut-selection-training/#training.

[2] Y. Brodsky, F. Carbognani and E. Melotti, "The use of immersive virtual reality and motion tracking in astronaut training and space system design," in *66th International Astronautical Congress*, Jerusalem, 2015.

[3] F. Nicolini, C. Scott, R. Seine and M. Wolff, "3D Visual Training for operations on-board the International Space Station and beyond," in *67th International Astronautical Congress*, Guadalajara, 2016.

[4] Y. Lonchakov, B. Kryuchkov, A. Kuritsyn, V. Sivolap, P. Saburov and I. Sokhin, "New approaches to cosmonaut training on the program of scientific-applied research and experiments aboard the ISS Russian segment," in *66th International Astronautical Congress*, Jerusalem, 2015.

[5] I. Sorokin, Y. Lonchakov, V. Sivolap and A. Kuritsyn, "Issues of crew training for interplanetary missions," in *67th International Astronautical Congress*, Guadalajara, 2016.

[6] G. Riva, F. Mantovani, C. S. Capideville, A. Preziosa, F. Morganti, D. Villani, A. Gaggioli, C. Botella and M. Alcañiz, "Affective interactions using virtual reality: the link between presence and emotions," *CyberPsychology & Behavior,* vol. 10, no. 1, pp. 45-56, 2007.

[7] C. Botella, R. M. Banos, E. Etchemendy, A. Garcia-Palacios and M. Alcaniz, "Psychological countermeasures in manned space missions:"EARTH" system for the Mars-500 project," *Computers and Human Behavior,* vol. 55, pp. 898-908, 2016.

[8] S. Bishop, S. Haeuplik-Meusburger, J. Guinead, R. Peldzus, "Bionomic Design Countermeasures for Enhancing Cognitive and Psychological Functioning and Crew Performance in Isolated and Confined Habitats," in *46th International Conference on Environmental Systems*, Vienna, 2016.

[9] W. IJsselsteijn, W. Oosting, I. Vogels, Y. De Kort, E. v. L. De Kort and e. al., "Looking at or looking out: Exploring monocular cues to create a see-through experience with a virtual window," *PRESENCE,* pp. 87-95, 2006.

[10] J. A. Wise and R. P. Taylor, "Fractal Design Strategies for Enhancement of Knowledge Work Environments," in *Human Factors and Ergonomics Society 46th Annual Meeting*, 2002.