IAC-19-D4.1.6

# Mixed Reality Architecture in Space Habitats

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**Abstract**

From assisting with assembling the Orion capsule to using highly immersive virtual environments for astronaut training, MR technologies provide a powerful mechanism to alter the perception of the physical world and deliver realistic personalized visual stimuli to users. In this paper, we discuss a novel strategy to utilize MR technologies as a design element to enhance the interior architecture of the space habitat and enrich the inhabitants' personal experience. We discuss two scenarios that entail long-duration missions as well as a customized experience for space tourists in the Low Earth Orbit (LEO). A series of spacecraft volumetric studies of the ergonomics associated with the application of MR technologies are reported. Physical, virtual and combined experiences are mapped within the volumes with respect to crew ConOps. The experiences are then analyzed and translated to architectural design requirements that inform criteria for the development of personalized MR- based interventions.

For the first scenario, NASA's 500 days on the surface of Mars mission is considered, which requires 600 additional days in microgravity transit inside the Deep Space Transfer vehicle, a 7.2 m wide hard-shell module. In this scenario, MR experiences are used as a stress countermeasure to help a crew of four to sustain psychological and behavioral health, maintain productivity, and stimulate teamwork and performance. This is accomplished by providing novelty in the habitat as well as designing content that can increase the volumetric perception of the environment.

The second scenario is presented in the context of space tourism where habitats with minimum physical interior design elements can be transformed into comfortable habitable personal environments. Bigelow Space Operations' B330 was selected as a reference site for a 12-day LEO tourism mission. We discuss a design approach that provides tourists with a high level of comfort by using projection-based MR technologies to customize personal spaces based on individual user preferences. The implementation of these elements can help minimize launch requirements and significantly reduce the time and cost, both in terms of development and maintenance, which can be particularly interesting in future space hotels with regular guest rotations.

The paper concludes with a discussion of directions for future research and design-based investigations. Compilations of mission-influencing factors such as launch mass and volume reduction per habitat, technology limitations and integration requirements are presented and evaluated by the level of importance for achieving mission goals and objectives.

**Keywords:** mixed reality, space tourism, stress countermeasures, habitat design

**Acronyms/Abbreviations**

International Space Station (ISS)
Low Earth Orbit (LEO)
Virtual Reality (VR)
Mixed Reality (MR)
Cave Automatic Virtual Environment (CAVE)
Extravehicular Activity (EVA)

## 1. Introduction

This paper describes a strategy to enhance the human experience during long-duration spaceflight through the implementation of mixed reality technologies. Our approach is particularly relevant in times when companies like Bigelow Space Operations are taking big leaps in space tourism activities. However, there are many challenges that need to be addressed in space habitat design for deep space exploration and commercial applications such as space tourism. These challenges include psychological problems, homesickness of Earth, and emergency and maintenance protocols training.

### *1.1 Psychological Challenges*

The different psychological problems that are closely associated with human spaceflight [1] are discussed below.

- *Reduced communication*: Reduced real-time communication with family and friends may pose serious problems for prolonged space flight missions and for space tourists with civilian backgrounds.
- *Space motion sickness:* Space motion sickness requires limiting head movements during the first few days of spaceflight, which may call for increased assistance for mobility in the first few days.
- *Acrophobia/vertigo:* Acrophobia/vertigo is a significant threat, especially for crews doing EVAs, Research has consistently shown that gradual exposure through simulations can help in dealing with such phobias [2, 3].
- *Stress:* Internal conflicts can be a stressor in a group or a shared environment.
- *Disorientation:* A sense of sustained tumbling or inversion/disorientation is common in astronauts.
- *Impaired sense of precision:* The lack of precision in predicting the different dynamics of navigation in microgravity is also common, e.g., how much push-off force is necessary to move from one point to another.
- *Eye-hand coordination:* Eye-hand coordination becomes partially impaired without the usual sense of balance and orientation with respect to gravity.
- *Unpredictability of dynamic reaction of vehicle:* The inability to anticipate the dynamic response of the vehicle or system to manual inputs creates problems while navigating the space habitat.
- *Post-flight disorientation problems:* During post-flight (few days to sometimes weeks), astronauts have reported feeling heavier than usual and having difficulties turning corners while walking or driving, trouble in bending and picking up objects; and feeling disoriented while landing on the ground after jumping.

*1.2 Homesickness of Earth*

On a press interview, Dennis Tito, the first space tourist, reported that the most profound moment of his experience was talking to his grandchildren [4]. In various psychological studies involving ISS crew, astronauts recalled their thoughts of home as being more intense than the wonder and beauty of watching Earth from space [5], as shown in Figure 1. Thoughts of home ranked more recurring than those related to fatigue or problems adjusting. These feelings of isolation and disconnectedness can become more acute in longer-duration space travel.

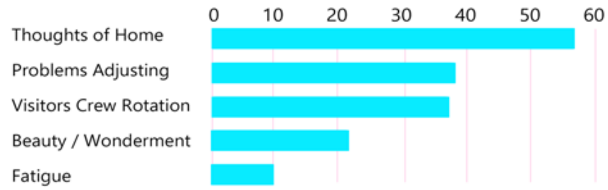


*Figure 1. Categorical distribution of journal entries by astronauts aboard the ISS [5].*

*1.3 Training passenger emergency and maintenance protocols*

Maintenance and repair in microgravity can be a difficult task. In this domain, Mixed Reality has been used for assembly and operation of ISS Racks [6] and for the Orion capsule assembly [7], among others. Likewise, space agencies have been using virtual simulations for crew training for quite some time [8]. Examples include the use of the Microsoft Hololens during assembly operations of the Orion capsule as well as the implementation of virtual reality as a training aid in flight simulators. These procedures focused on rehearsing on-board operations and refreshing randomly performed or new tasks.

## 2. Mixed Reality in Space Missions

Mixed reality (MR) or hybrid reality, is the merging of real and virtual worlds to produce experiences where physical and digital objects co-exist and interact in real time [9].

Mixed Reality is used in the ISS for crew training purposes and for maintenance and stowage protocols as part of the Augmented Reality Application for Maintenance, Inventory and Stowage (ARAMIS) investigation [10]. There have been proposals to use this technology as a psychological countermeasure to mitigate the challenging and harsh conditions of the space habitat by providing a mechanism to alter the visual appearance of the environment [11]. In addition to dealing with psychological stressors, MR can also help address other aspects, including:

- Redefining microgravity immersive experience
- Interactive social networking
- Instant provision of privacy
- Investigating and evaluating the benefits of using MR technology in space habitats

Different types of MR are available. Common media to experience this technology includes large displays and projection-based systems such as CAVEs (Cave Automatic Virtual Environments) as well as wearable VR headsets known as HMD or Head Mounted Displays. Although CAVE systems are expensive, hard to maintain, and are rapidly being replaced by HMDs, their working principle of a projection-based system was studied as a reference.

HMD technology is already available at the ISS. The preferred use of HMD is approximately thirty minutes per day, as prolonged use can be detrimental to crew health [12]. Figure 2 illustrates the number of scheduled sleep hours at the ISS and the preferred time for HMD use throughout a 24-hour period.

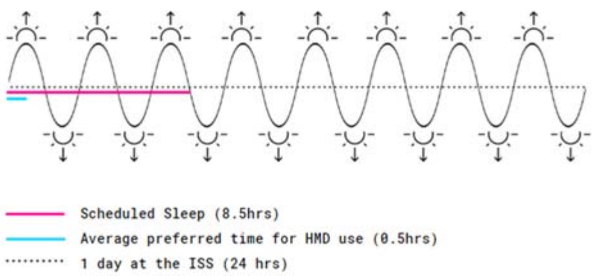


*Figure 2. Timeframe of HMD use in 1 day*

When put in perspective, this usage time of HMD is too short to yield any significant psychological benefits. In this regard, a ubiquitous projector-based system might be more beneficial. Considering mixed reality as a mechanism that can enhance and make space habitats more comfortable, we propose the use of projection-based systems. CAVE technology, although not practical for this scenario, is used as a reference to outline system requirements.

## 3. Selected MR technologies requirements and characteristics

The different types of Mixed Reality systems were compared by the various parameters that can affect the mission architecture. CAVE and HMD systems were used as reference to identify the pros and cons, as shown in Figure 3.

Geometry inputs were analyzed. Since the panel-based system may cause cluttering of the interior of the habitat, a comparative study was performed considering different projector-based systems. The various inputs, (shown in Figure 4) helped determine the feasibility of the projection layout for our habitat case study.

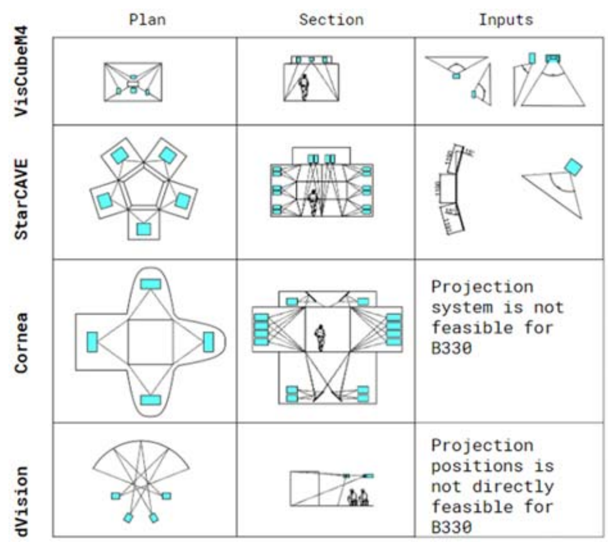


*Figure 4. CAVE Configurations and inputs*

For the purpose of this study, Bigelow Space Operations' B330 was selected as a reference habitat in the Low Earth Orbit. It is compatible to similar volume modules proposed by Axiom Space and Orion Span [13, 14]. The B330 was chosen for the versatile space

| | CAVE | | | | | HMD | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | visbox | Cornea | NexCAVE | StarCAVE | dVision | HoloLens | Oculus Rift | Occulus Go | Google Cardboard | Samsung VR Gear | Valve's Steam |
| Heat Generated | CAVE VR needs intense air exchange every 15 mins | | | | | Passively cooled (no fans) | cooling fan | Poor ventilation | Poor ventilation | cooling fan | passively cooled |
| Subsystems involved | screens, elaborate projectors, mirrors and supporting structure | Elaborate Sound System, PC, Microphone, Transmitter, receiver | 10 to 21 LCD panels, supporting frame, PC + graphics card | Screens, projectors, surround sound system | Screen, projectors, surround sound system | charger, cable, nose pads | joystick, no external sensor required | Joystick | none | Joystick | gaming controller |
| Resolution | ~2-24 Mpixels per screen | 16-Megapixel/screen , ~90-Megapixels/eye | 10 LCD panels , 10,000 x 1,500 pixels per eye | ~68 million pixels per user / ~34 million pixels per eye | from 1024 x 768 to over 4096 x 2048 | 1268 by 720 per eye | ~1 Mpixel per eye | 1280×1440 per eye | variable | 2160 by 2160 pixels per eye | > 1080×1200 per eye |
| field of view | 170 degrees | 170 degrees | 140 degree | 360 degree | 120 degree (H), 40 degree (V) | - | 110 degrees | 101 degree | - | 101 degree | - |
| Spare cost | much higher than HMD | | | | | 3,000$ | low | 200$ | 15$ | 129$ | - |
| users | Multi-user | Multi-user | Single | Multi-user | Multi-user | single user | single user | single user | single user | single user | single user |
| Projectors | yes | yes | no | yes | yes | no | no | no | no | no | no |

Pros

Cons

*Figure 3. Comparative analysis of CAVE and HMD*

missions that it has been proposed for, ranging from research to space tourism. With Bigelow's BEAM deployed at the ISS [15], the inflatable technology of the B330 can be considered space-rated, making it a reliable choice.

## 4. Design implications of MR integration in space habitats

The integration of MR in any type of a space habitat involves solving many problems related to geometry, availability of volume and space for system installations, and power consumption, among others. Utilizing Bigelow's B330 module will require addressing many case-specific challenges such as:

- Adequate sleeping quarters
- Projector systems installation
- Functional zoning
- Maintenance operations
- Tourism-related operations
- Air exchange system
- Heat rejection system
- Viewport location(s)

Although it is crucial to mitigate all of these challenges for a successful implementation, this paper focuses on the provision of adequate sleeping quarters (since it takes up a major amount of volume and can be conflicting to a public shared immersive environment) and the projector system installations. Power requirements and structural iterations and/or additions for the system's installation inside the B330 module will further define MR system parameters and limitations.

Different published design iterations of the B330 were studied: a commercial station design, the earliest and most detailed design of B330, and the design of B330 as shown in its full-sized Mockup [16-18]. All these design iterations have one commonality: the sleeping quarters are at the same location, as shown in Figure 5. This is a reasonable location, as the volume of the interior space is adequate for providing individual quarters, but not useful for any other function. Therefore, only space outside of sleeping quarters was considered for the deployment of MR equipment.

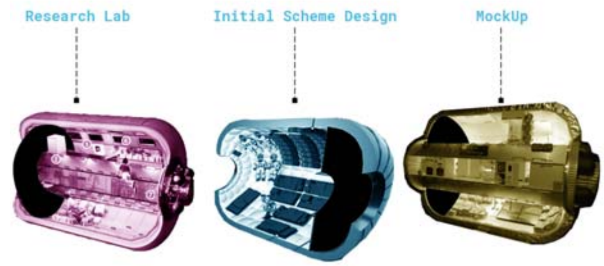


*Figure 5. Sleeping Quarter Location in B330 designs*

Iterations for projector positions according to the projector angle requirements and sleeping quarter positions are compared in Figure 6.

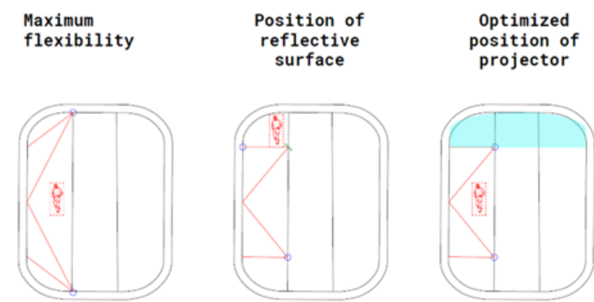


*Figure 6. Design iterations for locating projectors*

The next step was to calculate the number of projectors. To determine a number of projectors per screen and screen geometry, three CAVE systems were compared (see Figure 7). Based on the minimum number of projectors per screen and the screen size of the most relatable geometry two reference CAVE technologies

| CAVE VR System | Number of projectors per screen | Number of screens | Number of total projectors | Projector type | Power per projector (Watts) | Total power by projectors (kW) |
|---|---|---|---|---|---|---|
| VisCubeM4 | 1 | 4 | 4 | active stereo projectors | 815 | 3.26 |
| Cornea | 4 | 6 | 24 | 4K projectors | 470 | 11.28 |
| StarCAVE | 2 | 17 | 34 | 2K projectors | 1850 | 62.9 |

*Figure 7. Comparison of projector systems influenced by different CAVE systems*

were selected [19-21]. With these assumptions, the number of projectors to cover the entire space of the habitat was calculated to be 54, as illustrated in Figure 8.


*Figure 8. Number of projector calculation*

In the case of a cylindrical projection system, the number of projectors was reduced to 36 (see Figure 9) by extrapolating from the dimensions and number of projectors used in dVision projector system [22]. However, this is a hypothetical scenario where almost the entire internal surface of the B330 acts as a projection screen. Realistically, the projector-based system would be used only partially, using approximately two projectors per square meter.

The hypothetical maximum usage and more realistic usage are shown in the cross-sections of the B330 shown in Figure 10. The maximum case utilizes 36 projectors. However, for individual use two projectors are enough. The exact arrangement of these projectors will depend on the various mission operations.

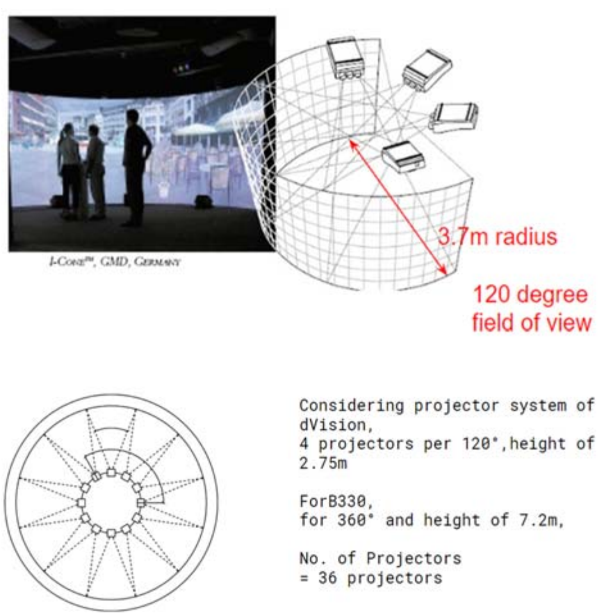


*Figure 9. Alternative projection-based system*

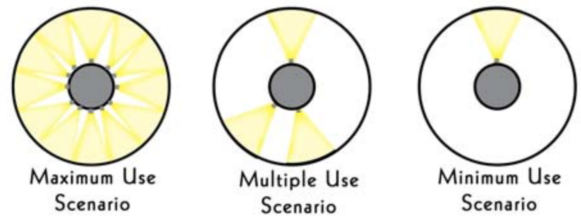


*Figure 10. Different use configurations in B330*

With a fixed number of projectors and their positions, power requirements can be defined (see Table 1). The power requirements were calculated for the maximum number of projectors within the entire volume of the B330. The geometry of the projector system would be installed using the pattern shown in Figure 11.

| CAVE VR System | Number of projectors | Projector type | Power per projector (Watts) | Total power by projectors (kW) |
|---|---|---|---|---|
| Proposed | 36 | 1024x768 dVision projectors | 900 | 32.4 |

*Table 1. Final immersive system details*

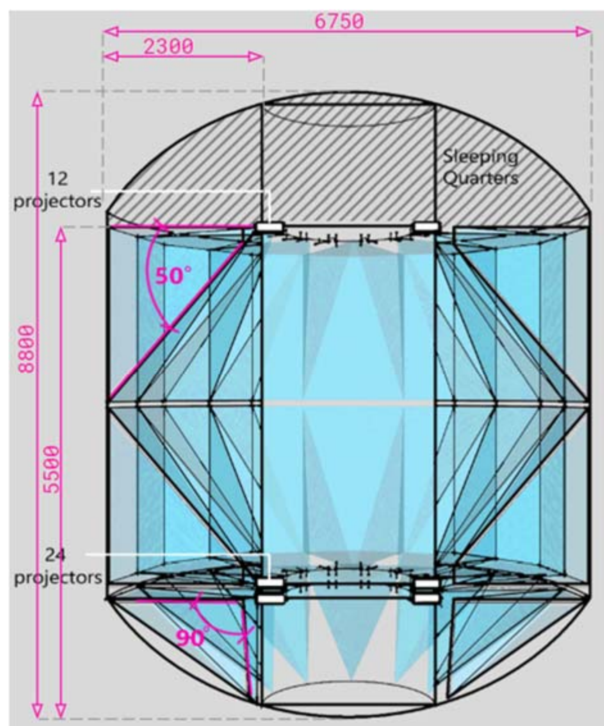


*Figure 11. Final configuration of projection-based MR system*

## 5. Discussion and Future research

Our research takes a holistic approach at the design of a MR system in the B330. MR-based interventions such as the ones discussed in this paper can have significant implications in prolonged human spaceflight missions such as the 500-days Mars mission. In this mission, four crew will have to live inside the small volume of the Deep Space Transport Habitation module for 600 days in microgravity, without any care package or any view of Earth. Psychological health will be a primary concern. In this regard, MR technology can play a significant role in mitigating psychological problems such as stress, isolation, and claustrophobia.

The strategies described in this paper can be used as a threshold or guideline for designing mixed reality experiences in a space habitat. However, we do not cover aspects such as:

- Power requirements of auxiliary projector subsystems and feasibility analysis of how much power needs to be dedicated to MR systems from a mission planning perspective as well as the implications in terms of number and position of projectors. This would also affect the interior layout of the habitat.
- Air conditioning requirements of projectors. The feasibility must be re-evaluated from the air exchange point of view.
- Design iterations considering different functional requirements can be performed as a final output.

The idea of an immersive space habitat can be tested and space-rated in upcoming launches, such as the scheduled launch of the B330 into low lunar orbit by Vulcan ACES by the end of 2022 [23]. Although in the scope of this paper, the versatile B330 was discussed as a case study, the MR technology can be tested with other space habitat modules. In addition, our approach can be tailored to support versatile missions. Using a projection-based system of MR in space habitats can support a wide range of functions including entertainment, team building, social activities, preparation for crew operations, assist with maintenance protocols, etc.

Like the former astronaut, Jay Buckey once said, "The more tools you can give people to maintain a good psychological state, the more successful the mission is likely to be" [24]. His statement resonates with our use of mixed reality technology as a mechanism to maintain the mental health and well-being of spacefarers, from simple enhanced experience for tourist missions to dealing with more serious issues in deep space missions. Future research will help to consolidate more aspects of mixed reality in terms of its feasibility in a space mission.

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