Mixed reality in the design of space habitats

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What kind of habitat is needed in an environment that is totally alien and likely to kill you? As we take the next steps towards a permanent presence off-Earth, the task will be to move from simply providing systems to offering meaningful habitats that go beyond provisions for mere coping and surviving to those that enable their occupants to thrive. Although long recognised as critical by psychologists, designers and mission planners alike, the optimal habitat remains elusive. Could the technologies of mixed reality and fractals help?

In extraterrestrial operations and design, the term habitability not only refers to the "general acceptability of the environment to the user" (Messerschmidt & Bertrand 1999), but must also aim to "promote optimal performance, physical and psychological health, and safety in long duration spaceflight" (Morphew 2001).

Habitability research for space has received little systematic attention so far, and design interventions for in-flight support have changed little since the advent of long duration missions. Upcoming crewed missions will be dramatically different from low-Earth orbital missions in both mission demands and the kind of individuals that represent the 'best fit' for such assignments.

▼ Immersive VR in the film *Ad Astra*.

In an environment that is comprehensively foreign to all prior human experience, and where almost any system failure will result in life-threatening consequences, any constructed living space needs to contribute to our adaptation to the challenges of living off-Earth. Such conditions will also present challenges unforeseen by mission planners and situations where residents will have to be resourceful and address problems in unconventional ways. For example, interior environmental features used on Earth may be unsuitable for different gravity environments.

De-stressing habitats

NASA has officially recognised the "risk of incompatible vehicle or habitat design" as a risk to human health and performance in space. The main drivers for designing spacecraft interiors evolved from a primary focus on survival to automation supervision (Loftus 1984), followed by a 'humanisation' of space hardware through designers, architects and psychologists with the advent of long duration missions in the 1970s (Harrison 2001).

Accordingly, habitability has been re-envisioned as a viable contributor to both active and passive countermeasures for certain stressors. For instance, in the deep-space setting, where the general reduction of situational stimuli (especially external cues) is unavoidable, various environmental design features sufficiently flexible to generate novelty can mitigate the monotony inside the vehicle.

Sameness, repetitive work and never-changing external environments can lead to the feeling of boredom (an emotional state often described as emptiness, meaninglessness, lack of interest and disconnection between the body and the mind), which frequently promotes dangerously risky coping responses (Suedfeld & Steel, 2000). The introduction of visual and auditory novelty - as a countermeasure for sensory deprivation - is particularly relevant in long-duration spaceflight considering the historically sterile and monotonous conditions of the vehicle habitat.

The general strategy for the development of psychological countermeasures is based on anticipating the adaptation of the user or the system to reduce stressors and stress. In this regard, environmental aspects and human factors including habitability are considered critical. From a design standpoint, Pew (2000) identified three basic components that bridge between behaviour and environment: the human component, the system component (man-made technical infrastructure) and the environment (natural context). Naturally, countermeasures to alleviate monotony and prevent boredom can be implemented at any of the three levels.

Various common countermeasures to monotony have proved successful in the context of orbital and relatively short-duration spaceflight – for example, delivery of 'surprise supplies', access to extended communication opportunities with family and friends, and opportunities to interact with media. However, deep space travel and remote bases pose new challenges, such as absence of resupply missions, communication delays, increase of crew autonomy and lack of direct visual contact with Earth. Thus, new strategies, concepts and solutions will have to be developed.

Mixed reality research

In the near future, existing technological innovations such as mixed reality (MR) systems

Habitability research for space has received little systematic attention

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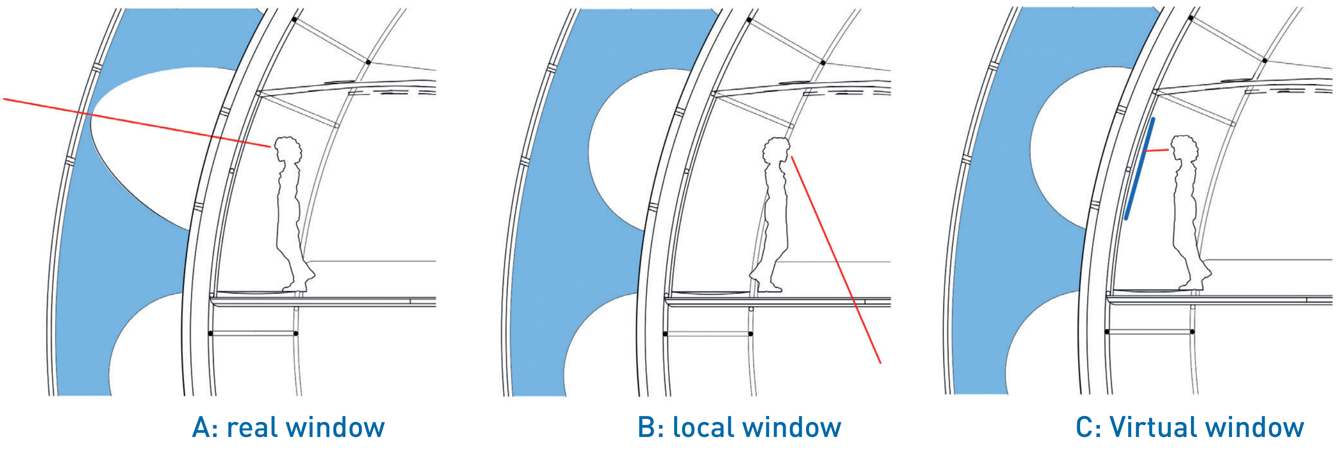


▲ Figure 1. Line of sight when using physical or virtual windows inside a notional space habitat (Sandra Haeuplik-Meusburger, ICES 2003).

▼ Astronauts living on the International Space Station for extended periods report that the openess and views of Earth offered by the Cupola contribute significantly to their general well-being. But such a luxury may not be practical on long-term, deep space missions.

are likely to play a significant role in maintaining the psychological comfort of residents in long-duration space habitats. MR technologies blend the physical and digital worlds by using real-time 3D computer graphics to immerse users in the environment. They seem to offer almost limitless possibilities for the creation and delivery of stimuli, while providing a tool to elicit and promote positive specific emotional responses when integrated into the interior design of spacecraft.

The term MR describes a spectrum, with the physical reality in which we exist on one end and the corresponding digital reality (that replaces reality with a virtual world) on the other end. There are various experiences between these two extremes that we call MR.

Today, a variety of technologies, ranging from portable devices to room-based systems, and from projection-based visualisations to head-mounted displays, can help to achieve an MR experience in a relatively comfortable and efficient way. An

interactive component or the sense of 'presence' - the feeling of becoming a part of the environment - defines the success rate of the experience.

The highest immersive system (involving diverse technologies such as light, sound and kinetic experiences) leads to higher levels of presence and, therefore, produces more significant psychological responses. Scientific evidence demonstrates that virtual environments stimulate emotional and psychological reactions even when a person is aware that the stimuli are not real.

MR will not only provide sources of entertainment and novelty, but also therapeutic needs. Studies in experimental psychology have revealed the effectiveness of mixed reality technologies as a tool to improve psychological interventions and promote well-being. One example of research using Virtual Reality (VR) as a psychological countermeasure in space settings is the EARTH system (Botella et al 2016), where various immersive environments were delivered via a headset to a group of astronauts to promote positive moods.

Such research is imperative in identifying both the opportunities and the limitations of MR. For instance, there is an interesting phenomenon in the area of visual perception where researchers have found discrepancies between spatial perception and judgment of distance in real and virtual environments. VR users consistently underestimate the dimensions of the environment and distances to objects.

In space, where depth clues are severely compromised, there may be similar misjudgements and VR could be a method for identifying and compensating for such deficits. On the other hand, the disconnect between virtual and actual reality in terms of visual perception provides interesting opportunities to study perception experiences that are difficult or impossible to replicate in real conditions.

Mixed reality (MR) systems are likely to play a significant role in maintaining the psychological comfort of residents in long-duration space habitats

Visual reorientation and visual motion illusions with moving observers may potentially be used to change the perception of real spaces in projection-based experiences (for example, by making certain areas look larger, brighter or just different). These conditions may become particularly attractive in the confined environment of space habitats.

Virtual window

Of great interest for habitat design is the potential to use dynamic and unobtrusive virtual imagery in common and private areas of the habitat to enhance specific architectural qualities and aesthetics of the living and work environment. One example is the virtual window (Figure 1).

The virtual window is a conceptual idea for providing an external view when the inclusion of a real window is not possible, involves additional engineering costs or when the outside view is limited (for example during deep space transfers). The positive effect of having windows is well-documented, so virtual windows in spacecraft will likely provide a similar restorative effect on the crew.

The design of space habitat architecture also presents opportunities for projection mapping technologies which may introduce visual novelty, augment the perception of physical spaces and provide countermeasures for psychological stimulation and the reduction of monotony. Ingeniously implemented projection-based visualisations in a confined space may have a significant effect on the perception of spatial dimensions and influence the perceived geometry of the overall volume of the habitat.

Another design example is the integration of virtual and real elements in a manner where they become accepted as real, which offers potential for full integration of immersive and mixed reality technologies in any designed environment and especially in the restrictive conditions of space habitats.

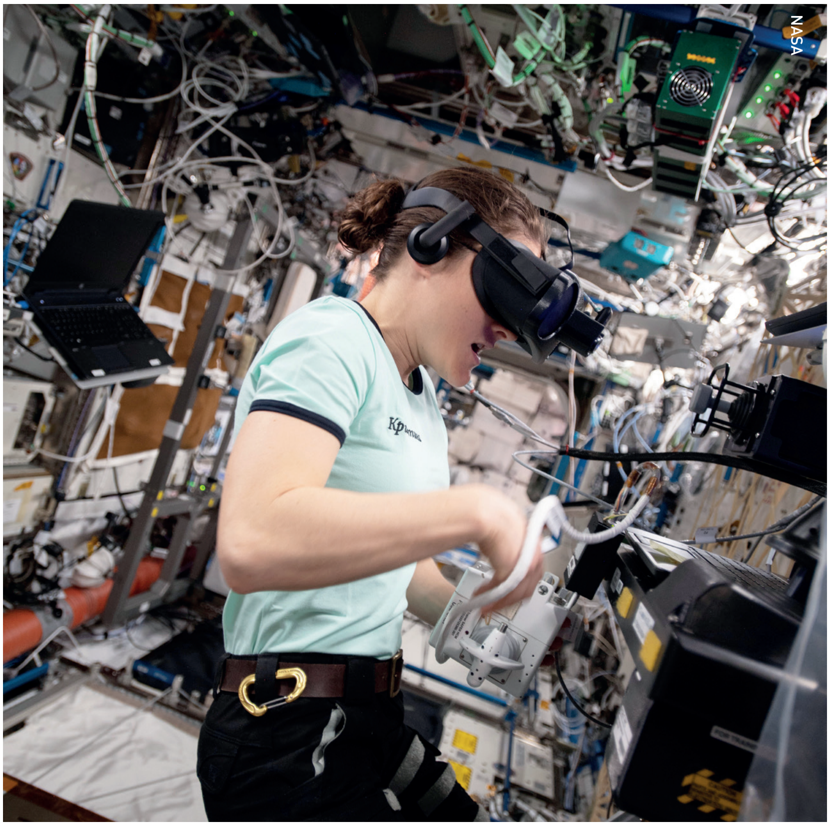
Immersive visualisation technologies have long been used in space applications, particularly as a training tool in building orientation and navigation skills. For example, VR was used to train astronauts in the repair and maintenance of the Hubble Space Telescope, as a pre-flight adaptation training tool and as emergency egress and evacuation training for intra-vehicular activities (IVA), enabling astronauts to build a mental map of the actual spacecraft. Likewise, Shuttle astronauts used VR extensively in combination with neutral buoyancy training for extra-vehicular activity (EVA) simulations.

Astronauts conduct VR training using headsets in pre-flight and in-orbit sessions. For example, figure 2 shows ESA astronaut Alexander Gerst in training at the 3D virtual reality laboratory at NASA's Johnson Space Center in Houston, Texas: he is using a VR headset to learn how to operate his spacesuit's SAFER emergency pack. Likewise, NASA astronaut and Expedition 59 flight engineer Christina Koch

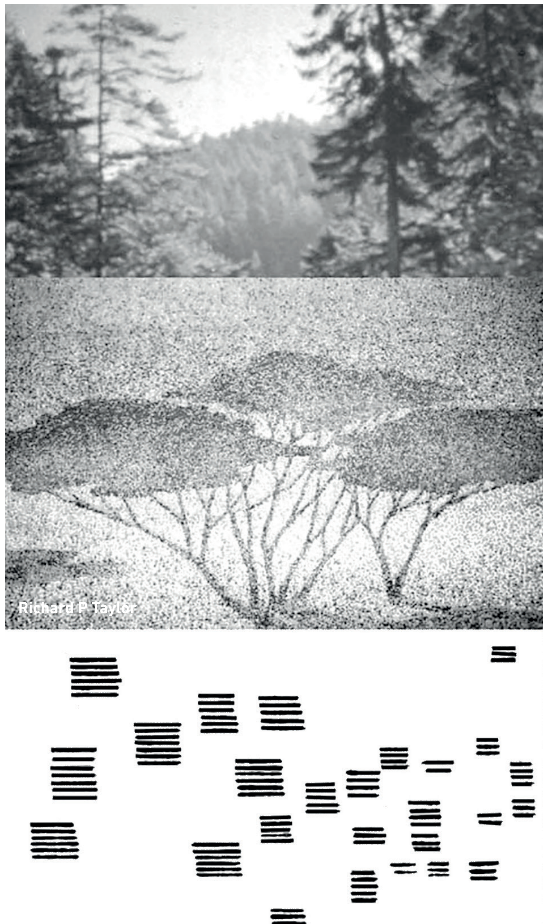
▲ Figure 2. Astronaut Alexander Gerst training in a 3D virtual reality laboratory.

VR Hyperspace Project/Fraunhofer IAO/Victor Brigola

▲ Creating a virtual reality experience. This proposal for long-distant air travellers could be adapted for future space farers.



▲ Figure 3. Astronaut Christina Koch wears a virtual reality headset for the Vection study carried out on the ISS.



▲ Figure 4. A photograph of a forest (top), an artistic rendition of a landscape (middle), and painted lines (bottom). From the article "Reduction of Physiological Stress Using Fractal Art and Architecture" by Richard P. Taylor, Leonardo, Volume 39, N 3, June 2006.

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(Figure 3) used a virtual reality headset for the recent 'Vection' study onboard the ISS to explore perception of distance, motion and orientation capabilities under microgravity conditions.

Despite these examples, MR has never been introduced in space or analogue missions as an integral habitat design component, where systematic studies of its application and effectiveness can be conducted beyond its training capabilities. To date, during actual spaceflight, visuals in MR-based interventions have required the crewmember to deliberately and actively engage in the experience (typically delivered through a head-mounted display), which may hinder its overall efficacy.

Strategically designed MR experiences can become a mechanism to deliver stimuli as psychological countermeasures in long-term missions, and ultimately advance immersive visualisation technologies to virtually enhance the physical habitable environment.

Fractal features

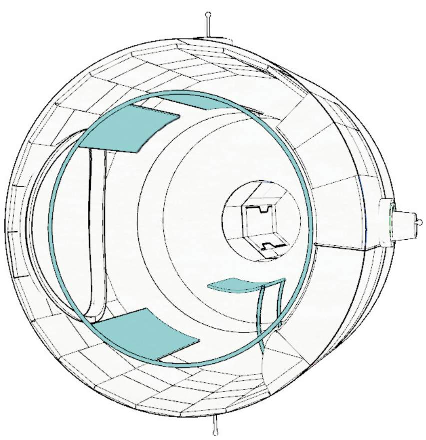
There has been a growing consensus since the early 1980s that the inclusion of 'nature' in living spaces produces beneficial and restorative effects. The 'green movement' promoted the inclusion of living plants, images of nature and natural textures, fabrics and textiles into almost every built social environment imaginable. It was, however, unclear why the inclusion of nature was beneficial; we simply knew that it was. The reason may finally be forthcoming, as convergent research from evolutionary psychology and externalised cognition suggest there are innate links between how we perceive our environment and how well we perform.

A central 'bionomic-design hypothesis' proposes that profound spatial and, particularly, fractal structures of benign ancestral human environments still act as a template for perceptual and cognitive processes that control our perception, memory and emotional management. Fractals are never-ending patterns made up of infinitely complex patterns that are self-similar across different scales; they are created by repeating a simple process over and over in an ongoing feedback loop. First recognised by the human eye through computer generated patterns called Mandelbrot patterns, they were soon identified in the natural world as well - for example, the petals of a flower or the repeating patterns of corn-on-the-cob.

Even more intriguing, research has found that mental processes associated with creative thought, stress reduction, performance and personal emotional management appear to benefit from instinctive perceptual, cognitive, emotional and psychosocial affinities associated with the fractals found in nature. And it's not just the presence of fractals but kinds and degrees of 'fractalness' in that particular environment (Figure 4).

The inclusion of natural features (plants, water features, etc) that has typified the 'green movement' in architecture has essentially accidentally capitalised on human preference for particular ranges of biofractal characteristics. However, we do not have to be limited to incorporating planters and fountains into our living spaces. For extraterrestrial habitats, such features can be resource and power prohibitive, as well as detrimental to internal environmental and structural conditions. An intriguing possibility now emerging is whether the inclusion of fractal properties within the optimal range is independent of the 'natural' content. Can we simply design environments that incorporate fractal features within that optimal range that do not have anything to do with vegetation, water, clouds or other nature features and still get the same psychological and physical benefits?

MR/VR-based architectural features may provide for the incorporation of fractal characteristics that represent interventions in space that do not require every crewmember to deliberately and actively engage in the experience that, to date, has typically been delivered through a head-mounted display.



Other MR technologies have yet to be studied as an integral design element of the habitat. In this regard, dynamic unobtrusive virtual imagery - particularly projection-based imagery - allows modified space perception of real spaces. It also enhances the interior architecture – using digital walls/windows, lighting, textures and colours, for example - and introduces novelty while remaining passive and relatively autonomous (Figure 5).

Implementing such capabilities means that future space habitats can be anything but sterile, boring and cold! They will become a true partner to humans in new worlds! ■

The virtual window is a conceptual idea for providing an external view when the inclusion of a real window is not possible

About the authors

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▼ Figure 5. Conceptual design for an Almaz space station utilising deployable surfaces and screens for projections.

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