# Even Space Architecture Doesn't Exist in a Vacuum: Starting from a Human Experience Perspective

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## Abstract

This is an architectural design project that akes a human-experience perspective towards space architecture design. The scope of the project is the design of a spacecraft interior for long-term habitation in microgravity. This design would align with multiple potential futures for human space exploration, including space outposts at the EM Lagrange points (stable orbits in the Earth-Moon system), or transit to Mars; however, the project does not specify an exact program in preference of a deeper theoretical exploration. This project studies architecture, human factors, and human machine interface in their relationships to each other and to augmentation and proxemics. This study produces the theoretical framework for the design project described and analyzed in this paper.

The design process utilized many digital media, including augmented reality phone and desktop applications, some of which used hand and motion detectors for interaction. One of the other primary media was a spatial, interactive installation, the analysis of which brought the unique conclusion of the design as a successful step in the development of an analog environment for testing human experience in an omni-orientational microgravity environment.

## Executive Summary

Human space architecture is at a critical moment as a discipline as we shift towards more sustainable long-term space exploration. This change is accompanied by a parallel shift from military-industrial driven design to more commercial design intentions. These changes call for a moment of reflection upon the discipline as the opportunity arises to interrupt the trajectory of human space flight and address its problematic history and effects.

While human spaceflight is nothing near a common occurrence now, both commercial and governmental units are looking towards its expansion. This architectural design project is a response to this moment in the discipline. In our design work, my thesis partner, Yundi Wendy Zhang, and I argue that this shift towards longer duration and higher frequency human spaceflight provides an opportunity for the dimension of human experience to come to the foreground of space architecture design.

Therefore, I argue that two specific aspects of the current and future human experience are especially important in structuring the design approach: proxemics of the digiphysical, and augmentation for sensorial and psychological engagement. These topics are used as frames to explore principles of architecture, human factors, and human machine interface. This process establishes a cohesive synthesis of the framework for the design work.

The first chapter will lay out the framework within which the design experiment responds. This begins with an analysis of certain principles of architecture, human factors and psychology, and human machine interface through three primary lenses of aesthetics, augmentation, and proxemics. Upon the synthesis of these ideas, the

specificities of the design, the methodology, and the processes will be elaborated in the second chapter. The third and final chapter takes a sweeping look back at the design process in the context of the first and analyzes the project as successful step towards testing space architecture design through an analog environment.

## Preface

This project has been challenging to narrow down to one concise topic, and I have spent a good number of hours questioning why this is so. I believe the answer resides in the architectural perspective itself: architecture demands of its practitioners an acknowledgement of the multifaceted natures of design. Human exploration of outerspace is one of many fields of design that has both a very complex history and present. As such, it has felt necessary to consider more factors throughout this project than is feasible to examine in a singular thesis such as this.

The fraught history of human space exploration finds its origins in World War II where the first space vehicles were little more than souped up missiles. While the Nazi V-2 program's influences on the beginnings of human spaceflight are well-documented, the lesser-publicized knowledge gained from many of the gruesome experiments performed on humans in concentration camps is arguably equally influential. These experiments included many which were used in the future of spaceflight, particularly those studying hypothermia and the effects of pressure (i.e. the vacuum of outer space) on the human body. This frankly disgusting abuse of humans is part of the difficult history of the first American flag on the moon.

But I cannot ignore this reality: the stark contrast between the militaristic origins of space exploration and its air of futuristic idealism marks a complexity that must be reckoned with. Furthermore, the current impacts of space exploration on our sociopolitical climate and global environment will only multiply if they do not become central to the design process. I would have liked to seriously grapple with these difficult issues, however, in preference of clarity, many of these remained at the sidelines of this design project.

This broader scope of human spaceflight was addressed in many of the early stages of research when Ariella Azoulay and Benjamin Bratton's sociopolitical theories were driving forces of the research and exploration. These ideas remained at the periphery of the project, serving as a reminder of the almost incomprehensible interconnectivity of individual systems, and the reckoning between these systems the and borders established in a hostile world.

## Acknowledgements

Thanks Wendy for being the most awesome and brilliant thesis partner I could ask for. You always helped challenge us to do better, be clearer, and most of all enjoy the process.

Thank you to my contacts at NASA, David Reynolds, Robert Howard, and David Smitherman for the amazing opportunities and conversations towards my goal of becoming a space architect.

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# Chapter 1

## Framework

The purpose of this design research project is to take a radically experience-centered perspective in the design of spacecraft. This paradigm shift learns from the history and theory of architecture, ergonomics and human factors, psychology, proxemics, human machine interfaces, and augmentation to synthesize these realities into a cohesive understanding of the human spatial experience in this future environment.

The word future is key here because—unlike typical near-future design projects where the planned future begins at the end of the design process—these ideas project beyond the next fifty to one-hundred years to an unknown, yet plausible, moment in time. Our modern environment is already informationally intensive, and as such "we increasingly rely on man-made technical systems to perform or assist our tasks."[1] This design project assumes a future where the trajectory of informational saturation has reached critical mass: the digital and informational environment has become so ubiquitous as to be inseparable from the physical environment.

The framework for design, described in this chapter, is separated into two sections for clarity: conceptual and referential. While this division does exist, there is of course some crossover between the two: where projects referenced for design also carried with them theoretical ideas that affected the conceptual intentions or vice versa.

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[1] Boy, Guy A., ed. *The Handbook of Human-Machine Interaction,* 2011, 53.

*Conceptual Framework*

We use the physical environment as a starting point for this exploration: beginning with architecture and proxemics. The term proxemics was first coined by Edward T. Hall, a social anthropologist, in 1966. He used this word to describe the "nonverbal use of space as a marker of culture."[2] This field of study now bridges the gap between communication studies and sociology, distinguishing the relationships among people in physical space. Hall's work is even the origin of a term which all of us at this moment are acutely aware of—social distancing.[3]

The social distance is one of four spatial ranges associated with the body. They are defined as follows: (1) intimate space, or the eighteen inches closest to one's body where heat and touch are easily exchanged, (2) personal space, one-and-a-half to four feet away from the body, where you stand when talking to a family member or close friend, (3) social space, in the range of four to twelve feet away from the body, or a comfortable range for a conversation with an acquaintance, and (4) public space, the area greater than twelve feet away from a person.[4] These spatial ranges define how loud one speaks, how much of another person they see and a variety of other factors. Furthermore, Hall acknowledges that these are culturally defined ranges, meaning that they differ across cultures and environments.

These factors of social space have substantial implications for architectural design, and it is therefore surprising to realize that they are not a standard part of the architectural curriculum. The relationships among people and with their environment are

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[2] McArthur, John A. *Digital Proxemics,* 2016, 16.
[3] This paper was written during the COVID-19 pandemic, April 2020.
[4] McArthur, *Digital Proxemics,* 2016, 20.

critical in architecture, and arguably moreso within the confined area of a spacecraft distant from Earth. Proxemics are dynamic, challenging the traditionally static nature of architecture. The—albeit incredibly simplified—primary purpose of the terrestrial built environment is to put a roof over our heads and in doing so, resist gravity. But in our increasingly media-based world, interactive and dynamic architecture has become a more important realm of exploration.

We don't yet live in a world where walls move according to our body movements, open to let in the cool spring air, or activate at our touch. Augmented reality is not a typical element of the current built environment, but the means are there for this reality to set in. The implications of this spatial reality are varied, depending on the method of augmentation: projections and screens offer a radically different spatial environment as opposed to head-mounted displays, the former being publicly interactive while the latter is more restricted to the private experience. Any form of augmented space will establish a set of rules for engagement, whether explicit or implicit, calling back to the ideas of proxemic relationships.

This spatial system, if part of the spacecraft environment, would be subject to the field of study known as human factors or ergonomics. This was discipline developed specifically in response to early aeronautics and astronautics, and now establishes the primary standards for such built environments. One anecdotal moment in the development of some of these guidelines parallels an important proxemic concept. In the early days of the Skylab missions,[5] the design proposals included a wardroom dining table

[5] Note: Skylab was a single-module orbital habitat operated by the United States which preceded the International Space Station. There were only three missions, operated from May, 1973 to February, 1974. This short duration was due to a number of technical failures and the eventual crash of the module out of orbit, luckily no one was injured in these missions. Source: Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects,* 2016, 193.

where the astronauts would sit with their backs towards one another, facing the external walls of their orbital canister rather than one another.[6] It was as if the astronauts had been reduced to "being simply another sub-system of the spacecraft." [7] In this case, they were treated as machines that had to routinely stop for caloric maintenance.

This kind of space where human interaction is discouraged is described as sociofugal space, and while privacy is certainly necessary in a spacecraft (or any other closed environment for that matter), socializing and social eating are central to human behavior.[8] To deprive people of this abilty is almost to negate their own being. Instead, certain areas of the spacecraft must be sociopetal, they should facilitate conversation and interaction.[9] The balance between sociofugal and sociopetal space is a necessary one in the spacecraft interior due to the physical constraints of a closed environment and their resulting psychological consequences.

Human factors therefore covers both the physiological and psychological bases of human space habitation. This includes an enumeration of the five primary hazards of human spaceflight and their associated remedies. These are: isolation and confinement, altered gravity, distance from Earth, a hostile or closed environment, and space radiation.[7] I would argue that while these are clearly concerned with many of the human aspects of life in outer space, they continue the tradition of efficiency at the forefront. They focus on the resolution of specific problems rather than a holistic human experience. These concerns were found and demonstrated specifically because of their impacts on astronauts's work performance and efficiency. Furthermore, this attitude towards

[6] Feireiss and Najjar, *Planetary Echoes*, 2018, 145.
[7] Ibid, 146
[8] McArthur, *Digital Proxemics,* 2016, 42.
[9] Ibid, 44.

efficiency has lead teams of designers to determine the "minimally acceptable net habitable volume."[8] The use of the words minimal and acceptable here reveal the prioritization of keeping cost as low as possible by reducing mass and space.[10]

Augmentation has been tested as a means of mitigating some of these noted hazards of human space exploration. For most people who have seen a popular science fiction film or two, this will suggest an experience such as the "Earth Room" in Sunshine (figures 1 & 2, next page). These simulation spaces are intended to soothe astronauts, particulary when agitated by the hazards of spaceflight relating to psychological factors: isolation and confinement, and distance from Earth. But the use of augmentation in human spaceflight is not confined to popular culture imaginations. Virtual and augmented reality are already used for training prior to flight and onboard the ISS for "rehearsal of docking procedures, research equipment handling, and refreshing randomly performed operations."[11]

Figures 1 & 2: the simulated "Earth Room" environment from Sunshine, 2007. Transitions reveal the reality.

[10] Note: These comments are not intended as a critique of the space architecture design process. These aspects of efficiency are *vital* to the survival of the astronauts and the feasibility of the program. Keeping the costs—environmental, monetary, and otherwise—low is an essential part of the engineering design process for space exploration.

[11] Bannova, Olga, et. al., "Projection-based visualization technology." 2019, 311. Note: one such example is a project I was involved in during the summer of 2019 at NASA Marshall Space Flight Center. Under the guidance of David Reynolds, Alireza Bahremand, Taylor Waddell, and I each played a role in the production of a virtual reality training program for ECLSS equipment maintenance on the ISS.

Dr. Bannova at SICSA sees much greater potentials for augmentation in space exploration. In a 2019 article, Bannova and colleagues comment on their on-going research regarding "implementation of immersive visualization technologies as a psychological countermeasure for space habitats".[12] The study used visualizations produced by projectors as design elements in a space to alter the perception of that environment; they acknowledge that one limitation of this study is the static positioning of both the projector and of the human subjects. However, the valuable information they gained was used to produce a set of recommendations for architectural habitats "with an emphasis on human factors and technology integration strategies."[13]

One other factor that Bannova's preliminary study does not address, but that is central to this paper, is interface or human machine interaction (HMI). As described by Guy A. Boy in *The Handbook of Human-Machine Interaction,* HMI is a relatively recent field of design study pertaining to the safety, performance, comfort and aesthetics emerging from the use of computerized machines.[14] A spacecraft can therefore be understood as one complex, life-sustaining machine. One that is always on. Thus, it follows that every interaction within and especially with the spacecraft is mitigated by that interface. If this machine is now producing levels of augmented, mixed, and virtual reality, then its capabilities are far beyond those of most machines with which we are familiar. The interaction with this machine surpasses the typical means of "interacting with a piece of software…through a computer screen with a pointing device and a keyboard." This machine is an augmented, spatial experience.

[12] Bannova, "Projection-based visualization technology," 2019, 310.
[13] Ibid, 310.
[14] Boy, Guy A., *The Handbook of Human-Machine Interaction.* 2011, 1.

This conception of the spacecraft as machine has massive implications for proxemics. The proxemics described earlier were those of Edward T. Hall, dealing only with the way that the physical environment shapes human movement and action, but John A. McArthur makes a compelling argument for technology's similar capacity. In bringing Hall's theory of proxemics into the digital realm, McArthur defines four roles of digital technology on the physical environment and its users. The first is to *inform* the use of the space by converting data (about the environment) into useful information (like wayfinding cues). Second, digital technology can *capture* information by gathering and translating data about the user(s) in the space and converting it into information. Third, it can *alter* the user's interaction and behavior both with and within a space. Finally, the digital can *control* a user's interaction with the space, even to the extent of directing emotions and behaviors.[15]

McArthur's theory of digital proxemics places a great amount of responsibility on the machine. And in the case of our spacecraft-as-machine, the role of the digital is at least equal to that of the physical on the human movement and spatial experience. Hence, we use the term *digiphysical* to describe this entangled environment.

To take this relationship a step further, we examine McArthur's comments on augmented reality in terms of proxemics as: (1) visualization, or simply the addition of visual information to physical surroundings in real time,[16] (2) search, or the use of new organizational patterns for receiving results to a query including place, device, and application,[17] (3) simulation, or physical graphics images and projection overlaid onto the

[15] McArthur, *Digital Proxemics,* 2019, 30.
[16] Ibid, 72.
[17] Ibid, 73.

environment,[18] (4) play, or the use of digital and physical elements to construct and structure game rules and interaction,[19] and (5) navigation, the use of an alternate routing structure to direct people through a space, such as GPS overlay.[20] Many of these factors assemble in different ways through the spacecraft design, playing unique roles in the use and experience of the space.

Dr. Bannova appears to draw a parallel between augmentation and proxemics again in describe three levels or ranges of augmentation to be useful in a spacecraft environment. While the primary goals of the study were to "achieve crew satisfaction and the operational requirements of the mission," the team's exploration into augmented reality extend much closer to the complete human experience rather than stopping at productivity requirements. Therefore, Bannova suggests first the level of personal mixed reality, which could be implemented through head-mounted displays or projections as an "affective or mood inducting medium" both customizable and private.[21] The second level would be public mixed reality, existing as dynamic and unobtrusive projection-based experiences. They are imagined as visual stimuli for "restorative effects," clearly catering to the more psychosocial hazards of space exploration (i.e. isolation and confinement, distance from Earth, and hostile or closed environments). The third level would be social mixed reality, differentiated from public in that it encourages social connectedness, collaboration, and teamwork, perhaps even "enhance[ing] the crew's connection to Earth."[22]

[18] McArthur, *Digital Proxemics,* 2019, 74.
[19] Ibid, 76.
[20] Ibid, 77.
[21] Bannova, "Projection-based visualization," 2019, 312.
[22] Ibid, 312.

*Referential Framework:*

Parallel to the conceptual research propelling this work is a set of built and unbuilt spaces referenced as precendents to this design project. The range of these projects is quite broad, from proposed space habitats by NASA engineers and designers, to radical Italian architecture projects seemingly entirely unrelated to space architecture. In this set of referenced projects, there are still certain patterns which arise.

Perhaps most notable are the substantial, and perhaps problematic, similarities between terrestrial and space architecture. No matter how futuristic or absurd the spacecraft designs appear at surface value: the projects fundamentally begin with the same groundwork. They draw from the history of architecture and spaces on Earth, spaces that are defined by a specific relationship to gravity. This is almost entirely irrelevant in the interior of a spacecraft.

Yet, even science fiction has struggled to escape the pull of gravity. The four film stills shown on the next page (figures 3 - 6) capture some of the tropes of sci-fi space architectures: the form of the cylinder or torus, a ground plane for walking (albeit somewhat flexible in 2001: A Space Odyssey), and sleek metallic surfaces. While the cylinder has proven to be a remarkably effective form for human space habitation,[23] the inclusion of the ground plane and walking movements in these films highlights the human tendency towards referencing the familiar for design. The term for this is skeuomorphism and it describes the use of familiar images and interactions to associate something new and different with a recognizable experience.[24] A good example of this would be the trash

[23] Häuplik-Meusburger and Bannova, *Space Architecture Education for Engineers and Architects,* 2016, 124.
[24] Göttling, Klaus. "Skeuomorphism Is Dead, Long Live Skeuomorphism." The Interaction Design Foundation, 2018. https://www.interaction-design.org/literature/article/skeuomorphism-is-dead-long-live-skeuomorphism.

can (now recycle bin) on the windows interface; the digital symbol and its congruent action, match those of the physical object and purpose.

Figure 3: Solaris, 1972, 01:42:25

Figure 4: 2001: A Space Odyssey, 1968 00:35:15

Figure 5: Star Wars IV: A New Hope, 1977 61:22

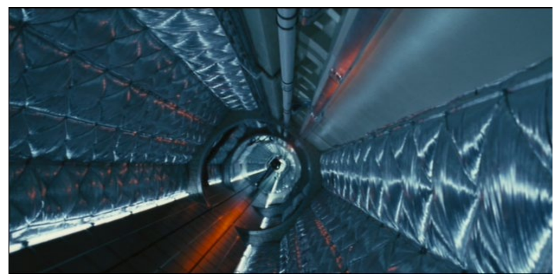


Figure 6: Sunshine 2007, 08:08

Figure 7: Stanford Torus, Rick Guidice, 1975

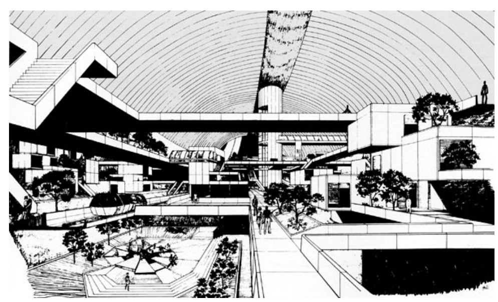


Figure 8: Stanford Torus, Patrick Hill, 1975

In the Summer of 1975, NASA contracted a number of architects and artists to produce renderings of potential future space habitats.[25] The two renderings above are both representative of what is now known as the Stanford Torus (figures 7 and 8, later adapted for Cooper Station in Interstellar, 2014). The most fascinating aspect of these

[25] Scharmen, Fred. *Space Settlements*, 2019, p 26.

renderings is the clear references to modern architectural design. In Patrick Hill's rendering (figure 8), the multi-layered urban fabric is reminiscent of Alison and Peter Smithson's "streets-in-the-air" projects, designed only a few short years before.[26] While these torus designs were intended to utilize artificial gravity (wherein *down*, as a vector of the human body is out), the similarities between them and terrestrial architecture (where *down* is in) remain uncanny.

Shown on the following page is a series of plan and section drawings for a potential habitat module for Mars transit. These were produced as part of a study by the Advanced Concepts Office (ACO) in late 2015.[27] The representational method itself comes directly from terrestrial architectural representation. Therefore, these drawing types relate specifically to the vertical orientation defined by Earth's gravity. In microgravity, designing through a consistent orientation produced by this drawing format is arguably limiting to the design potentials. The empty spaces shown in these drawings are residue of trying to fit terrestrial architectural language into a space architecture form. Furthermore, all of the people in the drawings are shown oriented the same way within the space, reducing the ways in which they can interact with their environment. This is not intended as a critique of the work, only to ask if there is a new representational form better suited to designing for microgravity.

[26] "TEAM X." 20th Century Architecture.
[27] Smitherman, David V. "Habitation Concepts For Human Missions Beyond Low-Earth-Orbit," 2016. https://doi.org/10.2514/6.2016-5216.

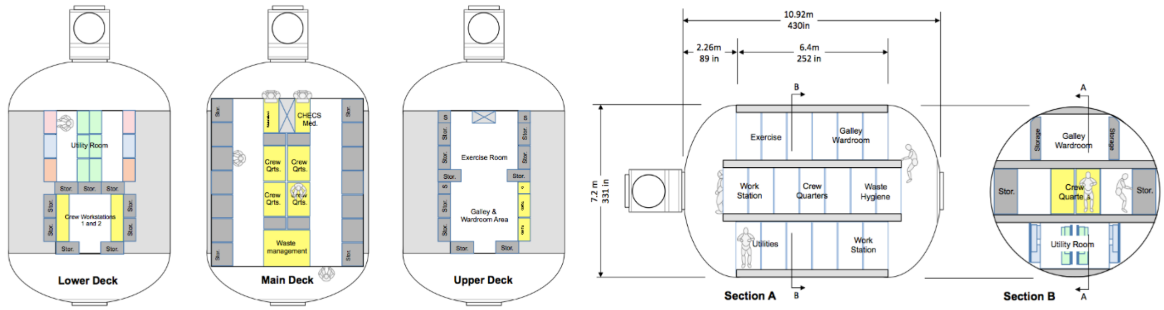



Figure 9: Plans and sections of a design for a Mars Transit Habitat[28]

One such form that we tested began to experiment with the infinitive environment. As a life-supporting, closed-system, there is nothing except the interior of the spacecraft: it is at once an endless interior and a tightly bounded condition. To enhance the spatial experience within the limited interior of a spacecraft, a continuous surface was introduced. There are two specific architectural projects which were referenced closely in the inclusion of and theory behind the infinite interior. The first is a project by Constant Niewenhuy, *New Babylon*. It imagines an architecture where "there is only the playful drifting of homo ludens (man at play) through an infinite and endlessly manipulable interior space."[29] This anti-capitalist art project, begun in the 1950s, had such a clear and uncanny resemblance to what we imagined the augmented space architecture interior could be, an active and responsive environment developed by its users.

Another such project designed during the late 1960s by Archizoom, *No Stop City*, is a fascinating endless interior world where "architecture was an environment that was constantly being reshaped, inscribed in the moment." This infinitive environment was produced before digital photo-editing softwares through physical models, mirrors, and drawings. Luke Caspar Pearson analyzes this project as a procedural world, or an

[28] Smitherman, David V. "Habitation Concepts," 2016.
[29] Pearson, Luke Caspar, "System Cities: Building a Quantitative Utopia," 2019, 72.

environment generated by an algorithm which composes elements and architectural components according to a programmed system.[30] He draws a parallel between this space and that of the quantitative worlds of automated Amazon warehouses and even to virtual spaces. Our project follows this trajectory a step further, beyond Cartesian position, orientation, and movement, defining typical physical and virtual worlds, into the omni-orientable, infinitive environment of the spacecraft.

[30] Pearson, "System Cities," 76.

# Chapter 2

## Design Methodology

The purpose of this design research project was to take a radically human experience-centered perspective in the design of spacecraft in response to the changing landscape of the discipline. This project assumes the importance of human interface and movement design as critical to the successful long-term habitation of outer space.

In contrast to the projects described in the referential framework, our design project begins by exploring the implications of human machine interface and gesture on the design of space architecture environments. Because we as designers do not have to work under the limitations of a professional structure (such as a commercial or government agency), we are able to question the typical processes of space architecture design and begin anew.

Our design process thus works in two directions and scales at once. We began from the relationships of objects, spaces, and human experiences to larger systems. For example, we found a way to represent the interconnectivity of driving your car, GPS satellites, and the politics of infrastructure. These explorations are intended to maintain the dialogue between history, human experience, and complex systems throughout our design process. A spacecraft, which can be imagined as a closed world, is as much a part of the internet of things as any other object or space. Engaging these aspects during design ensures that human spaceflight does not focus only on the requirements for safety and efficiency but is thought of as part of the larger human reality.

I digress from the primary argument for the next few pages to explain in more detail the concept, purpose, and outcomes of this representational tool.

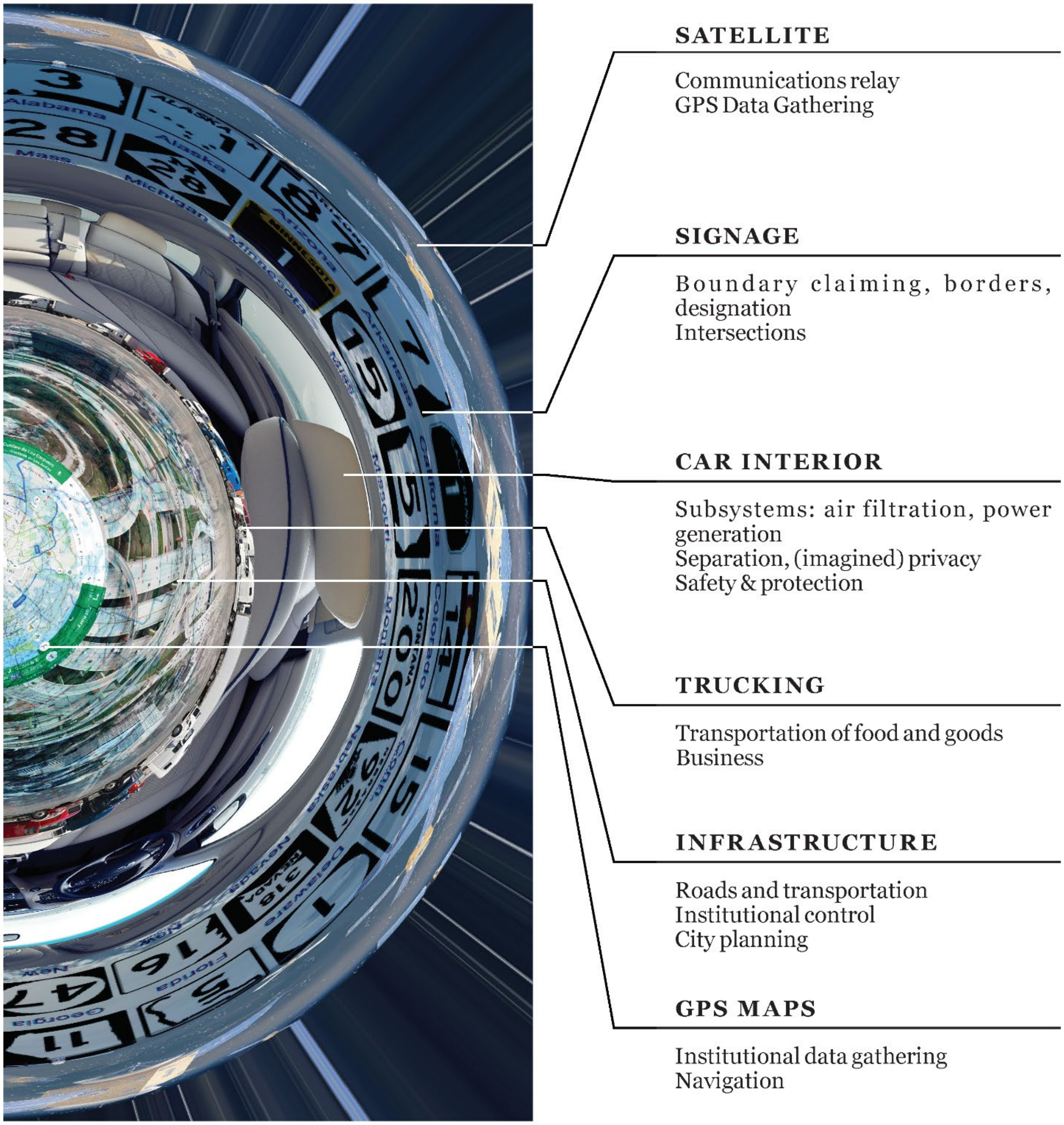



Figure 10: Car world explained by layers

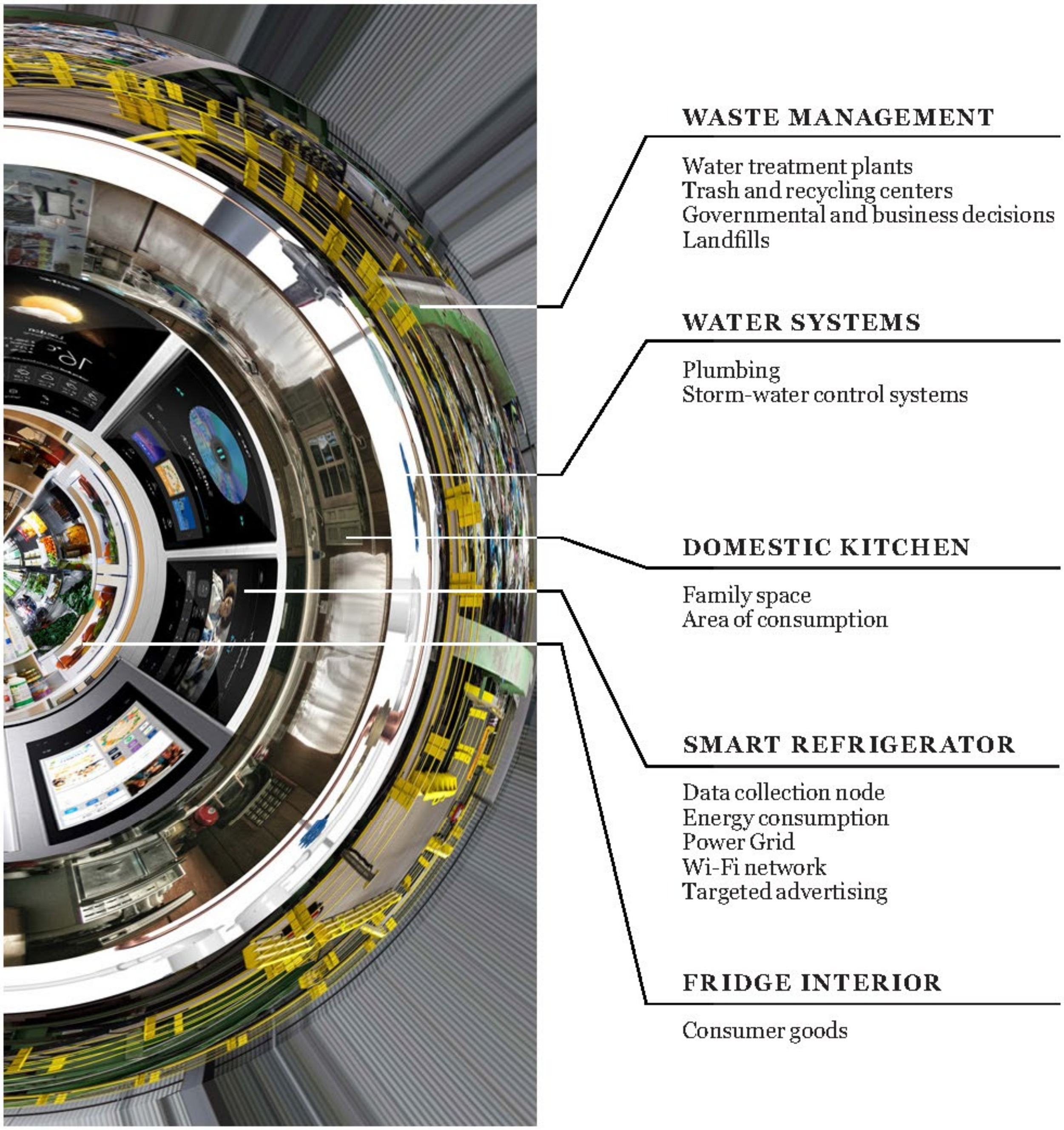
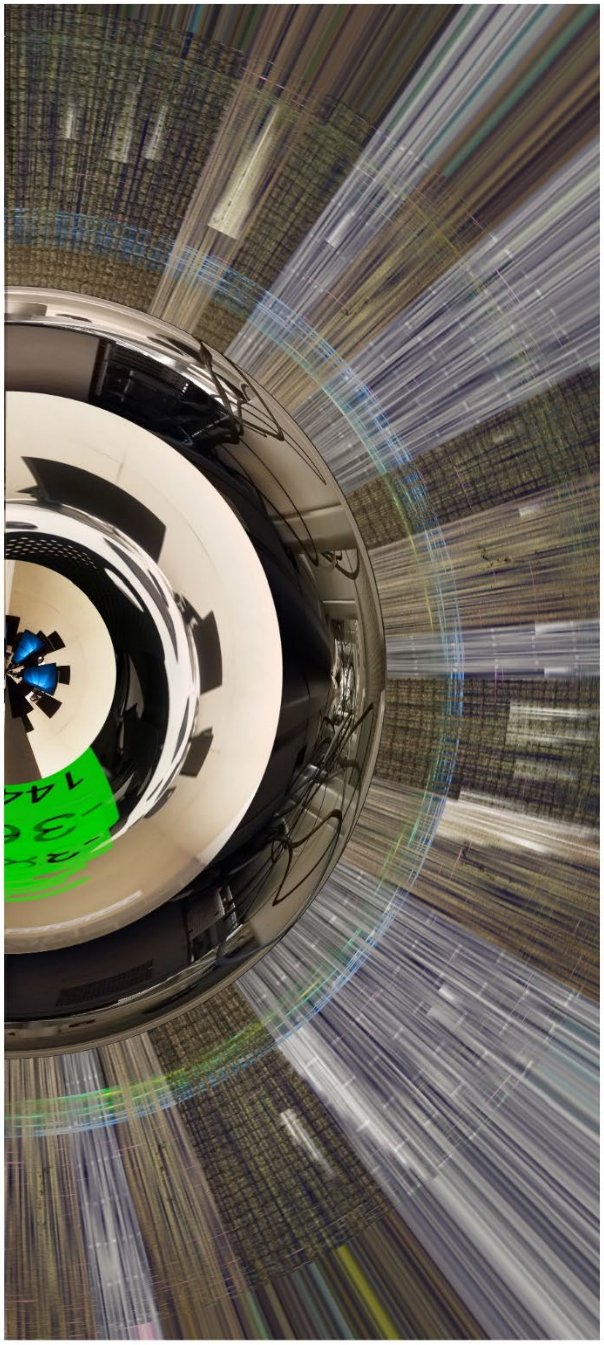



Figure 11: Kitchen world explained by layers



**COMPUTER LAB**
Monitors / Mobile Signals / Electricity Cables
Undersea Cable / Optical Fiber

**INTERNATIONAL SPACE STATION**
Life Support / Research Labs / Data Transmission
Solar Panel / Satellite Orbits / Governments

Figures 12 & 13

**GLOBAL SHIPPING**
Customized Ads / Ground Shipping /
Distribution / Oversea Route / Door-to-Door

**SMART LIGHT POLE**
Traffic Intersection / Face Recognition
Personal GPS / Surveillance / Traffic Data

Figures 14 & 15

At the same time as we examine closed systems at this expansive scale, we also approach the design problem from an intimate, human perspective. Instead of beginning with practical constraints and then making sure that the human fits into the picture, we study human gestures and movements in a microgravity environment first. Using the framework of proxemics and digital proxemics (or the study of how spaces and technologies affect the way we move),[31] we design the ways in which space architecture can—and should—differ from terrestrial architecture with respect to digital and physical space and interaction. These differences originate with the condition of microgravity which allows for omni-orientation. Unlike our familiar x-y exploration of terrestrial space, a microgravity environment produces radically three-dimensional and extraordinarily different human movements and gestures. Directionality is no longer a limiting factor to design and instead becomes an opportunity for innovation.

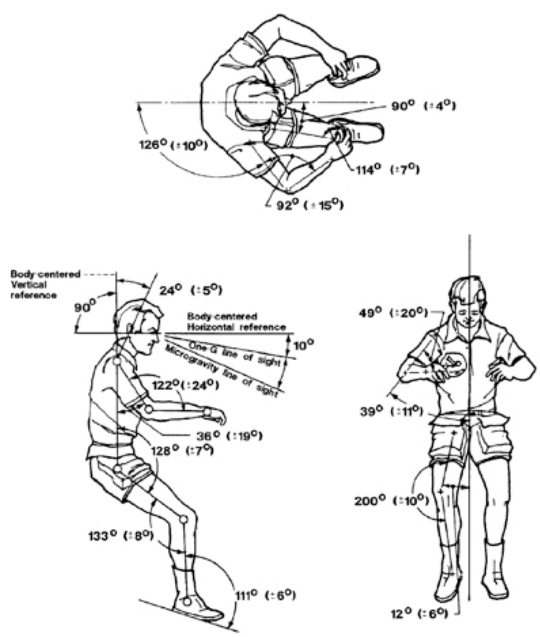



Figure 16: Neutral Body Position (NBP) in microgravity

[31] McArthur, *Digital Proxemics,* 2016.

Figure 17: A study by author of various body positions and movement capabilities under microgravity.

One of the intermediary experimental products of this collaborative architectural work was the production of an experiential environment installation, outfitted with a digital augmentation tool that informed the use and experience of the space. Employing mixed reality in this way produced a level of sensorial engagement that is missing in prior space architectures.

This installation is the moment where the representation tool and the study of human gesture reconvene in occupiable space. This tool augments the physical environment in the creation of what we are claiming is the developing digiphysical reality. The digiphysical in outer space takes the known necessity of the physical environment which must sustain human life and adds to this the growing importance of digital augmentation. The unknown of the digital space holds potentials for both accessibility and control, and for sensation and psychological experience.

# Chapter 3

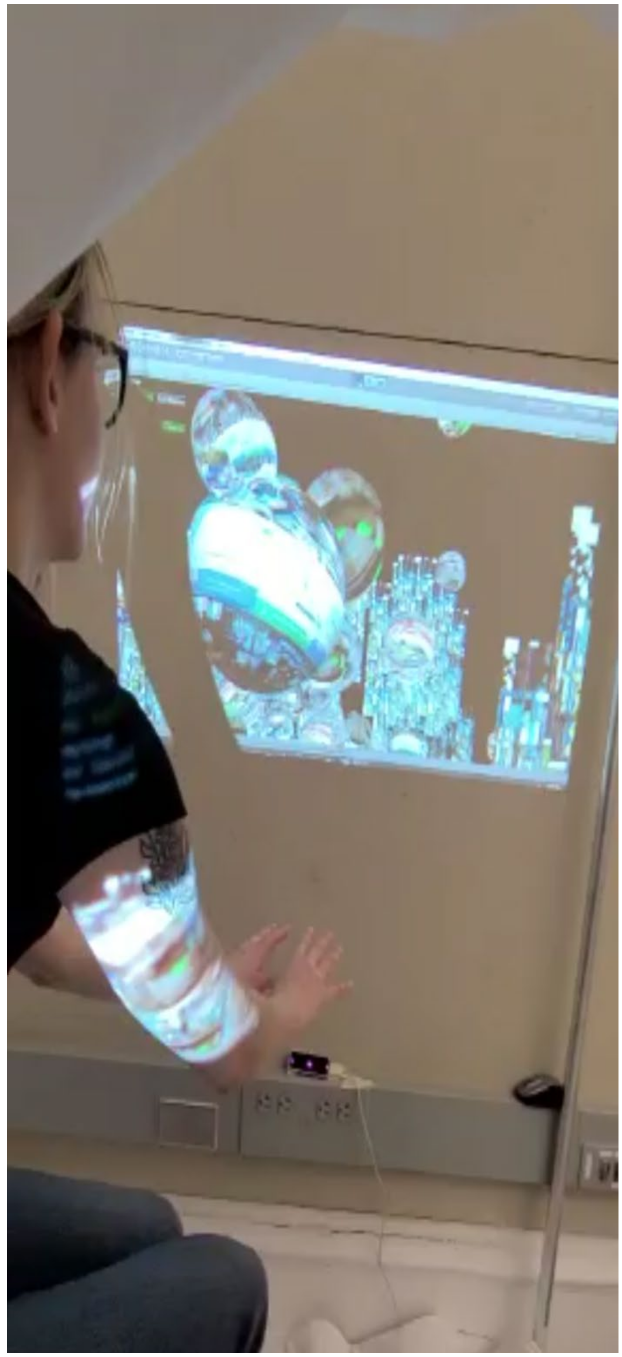
## Analysis and Conclusion

The following pages consist of images and descriptions of the architectural thesis midreview installation experience.

Figure 18: Dean Michael Speaks experiencing the design installation

This image is taken from the door to the room which was filled with the installation piece. In order to enter the space, a user must bend down or perhaps crawl before landing in a seated position or leaning back to experience the first of the projections.

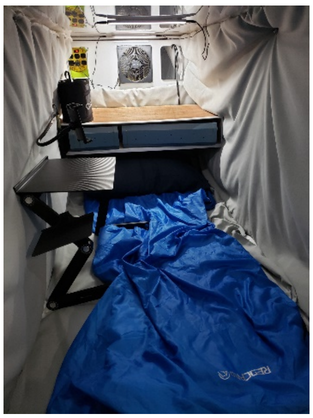
Figures 19-21: clips from a video of the installation implying the necessary crouching to enter the space

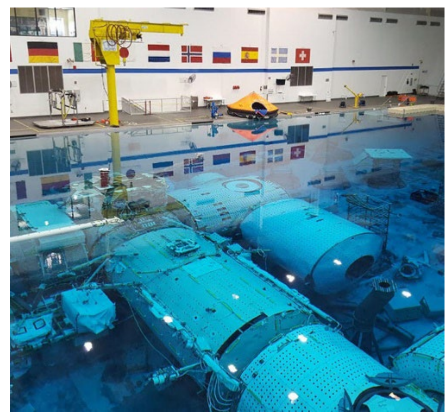



Figures 22 & 23: photo showing the layering of fabric to create a uniquely navigable environment, example usage of the author-developed augmented reality application allowing the user to interface with the environment and information

Figures 24-26: examples of the aforementioned augmented reality application developed by author in Unity. These images depict different gestures used to interface with the system

This installation can be thought of as an analog environment to that of the spacecraft interior. Analogs and mockups are central to the experiemental process of designing for outer space habitation. NASA uses multiple different analog environments for their research including deep sea habitats, to McMurdo station on the South Pole, and the HERA (Human Exploration Research Analog) project. These range from testing crew autonomy and behavioral studies, to movement in zero-g as in the Neutral Bouyancy Lab and everything in between.[32]



Figures 27-29 (left to right): an Orion sleep capsule low-fidelity mockup by Robert Howard, JSC; HERA habitat, and the Neutral Buoyancy Lab (NBL)

The production of this analog environment was a unique physical and theoretical challenge. There were many limiting physical factors including time, cost, resources, and even my ability to sew. But the theoretical challenges that the production of this environment posed were far more interesting and certainly helped to propel the project towards its eventual clarity.

One of the first theoretical stumbling blocks was the fact of the installation being constructed on Earth in the year 2020. This is put most eloquently by Guy A Boy as he

[32] Arnaldi, Smith and Thropp, "Human Behavior During Spaceflight," 2015, 29.

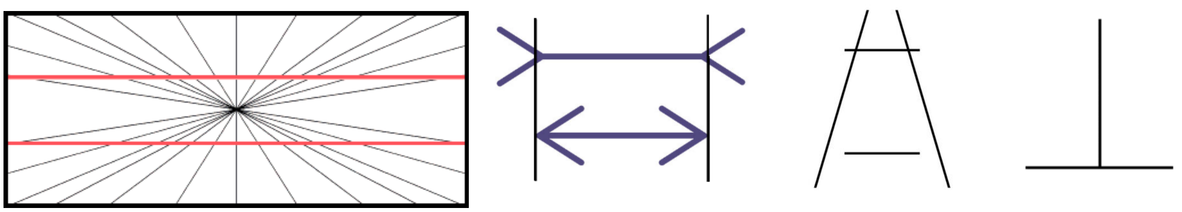
describes that "the world in which we design comes with some already installed basis: physical (equipment, devices), social (laws, customs, norms), and cognitive (habits, education). Even the users are "second-hand": they are not new to the system being designed in the sense that they have already been educated and trained within the current system."[33] This has some interesting implications for the design process, especially in establishing and understanding the time frame for this project. While this design has been completed under the circumstances and using the resources available in 2020, the designed environment would be occupied and used by a future generation with an ostensibly very different framework of life experiences and technologies.

Therefore, the installation produced for the architectural thesis midreview faced some rather interesting conflict and criticism. First, this spatial experience fundamentally does not work on the Earth's surface. As the users had to crawl and climb through the strange fabric environment, they were frustrated that their movement was hindered. This contradiction was a design concern we questioned frequently, because the spatial experience of the installation was intended to be as close of an approximation to that of the spacecraft interior. Both spaces must define user movements, actions, and behaviors in the space, and the continuity of surface and relationships between closed spaces made sense to carry into this social and interpersonal analog environment. As such, the designed installation is incredibly like the future spacecraft interior, and yet dramatically different. Encouraging people to move as if in microgravity while under the pull of 1-G is a challenging experience to both the body and mind.

[33] Boy, *The Handbook of Human-Machine Interaction*, 2011, 165.

This incongruity of physical experiences has been tested through scientific experimentation on what is described as the Subjective Vertical. This is a perceptual knowledge derived from two sets of data which establishes a person's orientation in space according to visual and physical input separately. These sets of input arrive at the brain as the Subjective Visual Vertical (SVV) and the Subjective Haptic Vertical (SHV), and they depend on the human's evolutionary history of life on Earth.[34] Gravity has been described as "a strong prior," such that "Earth-discrepant gravity conditions" greatly challenge visual and physical perception. Everything from perception of time and movement speed to linear perspective optical illusions is affected by the body's relationship to its environment through the subjective vertical.[35]

Figures 19: Four of the linear perspective optical illusions which have been proven to affect astronauts less frequently in zero-g than they do on Earth.




Following this understanding of the relationship between gravity and spatial perception, the difficulties which users had in the analog environment were a reasonable outcome. The proxemics of the digiphysical installation required a different set of navigational movements to encounter the space, much like users would experience in the spacecraft environment. This was a clear reminder of the necessity to orient. In an environment both physically different from our standard living environment (curved and

[34] Fraser, Makooie and Harris, "The Subjective Visual Vertical and the Subjective Haptic Vertical Access Different Gravity Estimates," 2018.
[35] Björn and López-Moliner, "Gravity as a Strong Prior: Implications for Perception and Action," 2017, 4.

continuous surfaces one must crawl over and under) and augmented to such an extent of overwhelming digital and visual information, there must be exist an opportunity to stabilize.

This stabilizing, orientational element is the structural and *infra*-structural system of the spacecraft: defining both the physical space, and the digital augmentation amongst it. This is the physicalization of the "web," and it is the matrix of vertices and edges which form the continuous surface environment. Therefore, the digiphysical environment serves to both inform the user and alter their interaction with the environment, to use McArthur's terminology.[36]

[36] This is explained in detail in page 7 of the thesis.

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## Critical Statement

This statement serves both as a reflection upon and conclusion to the prior work. Most of the direct references for this work are elucidated in the referential framework portion of chapter one, but there are certainly many creative influences that have led me to work on this project and do so in this way. Most notable to someone outside of the discipline of architecture might be the interdisciplinary nature of this work. This is actually incredibly central to the field of architecture, especially the way that I was taught it at such a design-based school. Architecture, as it was instilled in me, is both a liberal art, a visual art, and a science, and much more.

The work that I have done over the course of this project therefore references more than strictly "architectural" works, to theoretical texts, engineering specifications, and beyond. Two references which I encountered later in the process, Dr. Olga Bannova, and Dr. Luke Caspar Pearson, are both investigating some of the very specific ideas I am involved in. Dr Bannova's research into augmented and mixed reality for outer space implementation validated my own interests and beliefs in this developing field. Dr. Pearson's work almost immediately stood out to me as parallel to the interactive interface environment of our design, but existing in the universe of game design rather than outer space.

Many of the works referred to in this project were referenced at a series of different times throughout the course of the work. For example, Constant's *New Babylon* project and Archizoom's *No-Stop City*, were both referenced early in the design and research phases. Much more recently, I discovered the article "System Cities" which elucidated further why we were drawn to and had referenced these projects in the first place: they were reflections of our project across different times.

This project was, if it isn't inherently clear by the structure of the paper, primarly theoretically driven. This was a conscious effort wherein my thesis partner, Wendy, and I discussed and wrote back and forth over our ideas and research in determining and evaluating every decision. Many times we still made intuitive decisions, but we always returned to our core ideas and reevaluated what we were doing as such.

There were many critical turning points, sometimes circular ones which serendipitously related our current work to ideas we had thought were lost, other times these challenged the entire notion of the project. The most notable moment of this would be the shift to a fully digital semester due to COVID-19. Prior to this, the design intention had been to produce a fully inhabitable 3-person architectural installation, outfitted with projections and interactive augmentation. This type of physical construction would have allowed for a more explicit interaction of the digiphysical. Although this was ripped out from under us, we were able to build a prototype for our architectural midreview, and the necessary rethinking of the project served to push us in a very different, yet equally productive direction. I was able to critically evaluate the installation's successes and failures which I think allowed for a level of analysis that I would otherwise not have reached with this work until months later.

## List of Figures

## Glossary

Augmented reality – describes a type of augmentation which overlays digital information or visuals on top of the physical world through some sort of interface or device

Digiphysical – the term used in this paper to discuss the complex interrelationship of the digital and physical environments due to the changing technological realm

ECLSS – Environmental Control and Life Support Systems, a NASA program

Human Factors – a field of study examining human physical and physiological needs, particulary in built and engineered spaces

Internet of things – a phrase describing the current reality where all objects and systems are related and affect one another by the network of information

MHV – Minimum Habitable Volume, the minimum required space in which humans can live and work in a spacecraft

NHV – Net Habitable Volume, the total

Proxemics – the study of how spaces affect the way we move and act

SHF – Space Human Factors

SICSA – Sasakawa International Center for Space Architecture at University of Houston

Space architecture – the design of habitable environments for outer space or other planetary bodies

Virtual reality – describes a type of augmentation which is fully immersive and digital