AR4ETA010
Extra-/ Terrestrial Architecture

From Survival to Living: A Neuroarchitectural Approach to Lunar Habitation

A1 Report (Draft)

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Abstract

As humanity transitions from temporary lunar cells to permanent colonization, the fundamental challenge of space architecture shifts from basic survival to mental well-being. While current space engineering prioritizes life support over the qualitative mental experience, this research instead proposes a neuroarchitecture framework for lunar habitation that specifically addresses the “Missing Plumb Line”, the chronic cognitive dizziness caused by the absence of Earth’s gravity vertical.

Based on human-centred design approach, this study investigates how to keep the mind strong as part of “space resilience”. This resilience is fostered through the implementation of “Visual Anchors”—deliberate geometric visual cues that provide the brain with an artificial sense of orientation and verticality, preventing the spatial “flips” and illusions common in low gravity.

The design utilizes the “Oblique Function” to replace traditional floor-wall hierarchies with sloped, curvilinear surfaces. These surfaces engage habitants through muscular tension, providing them with a constant sensory alternative for the “plumb line”. The volume is generated through computational design that follows Voronoi (closest neighbor) and Gyroid (minimal distance) logics, which optimizes both structural integrity and sensory complexity. Finally, the structural realization of this environment employs In-Situ Resource Utilization (ISRU) and Swarm Robotics.

More than the habitat itself, the project also aimed to indicate a guideline for lunar lifestyle, a consciousness that the built environment is more than physical entity but also users’ cognition.

Key words: **Neuroarchitecture, Low-gravity, Visual cues, Cognitive design, In-Situ Resource Utilization (ISRU)**

Part.1 Introduction (what and why?)

1.1 Problem Statement

Beyond 'surviving' to 'living':
Now we landed on the Moon, then what[1]?

Space engineering determines whether we can ‘survive’ in outer space, the problem now goes to how we can ‘survive.’

Is it like in the spacecraft “Orion?” Astronauts need to live in $9m^3$ of habitat volume for 10 to 21 days for Artemis II mission. It seems bearable to live in such small area for 10 days, but what about longer missions?

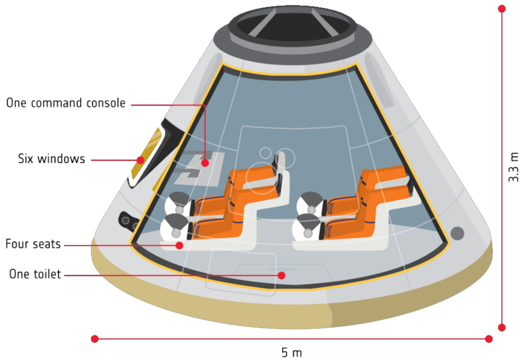

Fig.1 Orion: crew capsule. ESA

The design of the Mir space station represented space architecture in Low Earth Orbit. By carefully design modular functions, the station achieved certain efficiency in survival and research. Architect Galina Balashova focused on the psychological well-being of crews on long-duration missions, by defining “up” and “down” with dark green carpet floor and white ceilings, but forced the crew to spend nearly all their time on housekeeping[2].

Maybe the concept of “up” and “down” should not be defined in the first place.

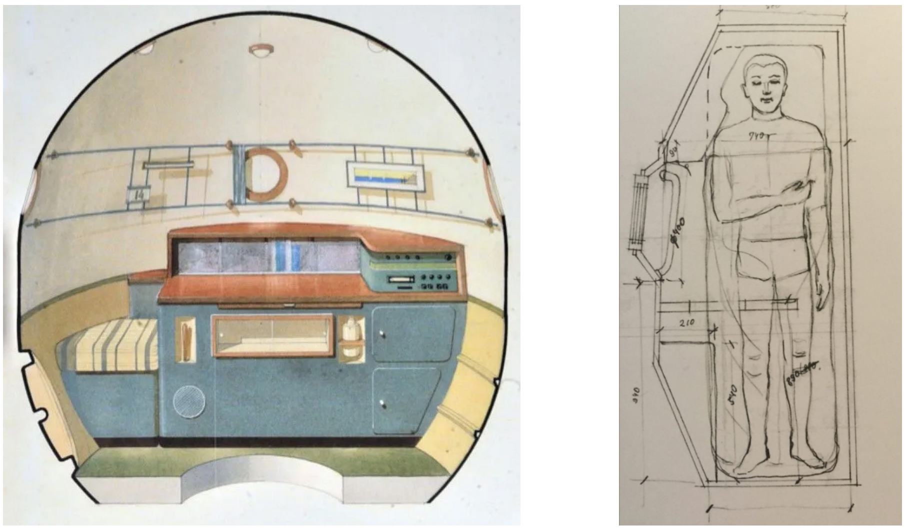

Fig.2 Sleeping pod. Galina Balashova

1. MIT Media Lab (2024). Moony Tubes.
2. Balashova, G. (1980). Topography design for the Mir space station. http://kvadratinterwoven.com/out-of-this-world-the-space-age-designs-of-galina-balashova

Missing of 'Plumb Line':
Cognitive disorder due to lack of gravity vertical

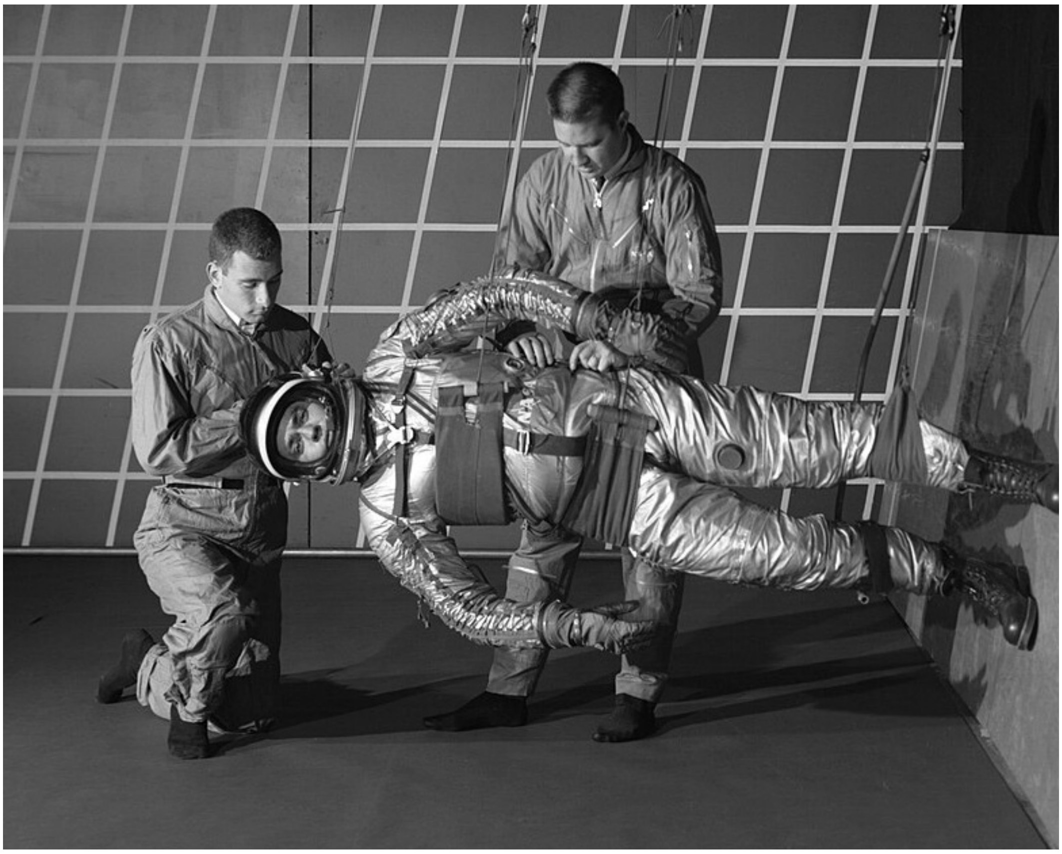

Fig 3: NASA testing moon gravity cognition, in a horizontal way

In order to define the problem, I looked back at the fundamental difference between earth and moon. Gravity is one of the major issues. Morfoisse investigates how gravity influences our brain's internal "map" of three-dimensional space, and challenged traditional views with the idea that this 9.8g "gravity" is exclusive and fundamental to the earth that affects all interpretation in all sensory inputs.

As a result, Due to low gravity, the human vestibular system (in inner ear) becomes disordered, and the brain can no longer rely on gravity as an absolute reference for "below"[3]. The Apollo 11, 12, and 14 astronauts also reported multiple serious visual misjudgements while walking on the lunar surface, that their perception of "far" and "close" failed to match with their own previous cognition on earth[4].

3. Morfoisse, T. et, al. (2024). Modality-Independent Effect of Gravity in Shaping the Internal Representation of 3D Space for Visual and Haptic Object Perception https://www.jneurosci.org/content/jneuro/44/13/e2457202023.full.pdf
4. NASA. (1971). Visual Optics in Space Flight. https://ntrs.nasa.gov/api/citations/19710024584/downloads/19710024584.pdf

How can we design without the “plumb line”?
To improve cognition in a monotony environment where the brain gradually abandons the “plumb line” of the earth

In 2016, an experiment titled “Visual gravity contributes to subjective first-person perspective,” investigated how the brain uses visual “gravity” cues to determine where “you” are located and from what direction you are looking at the world. The conclusion points out that gravity is a “multisensory” anchor. We don’t just “feel” gravity with our inner ear; we “see” it in the environment. When visual gravity conflicts with physical gravity, the brain can actually relocate the subjective first-person perspective, providing a scientific explanation for “out-of-body” sensations or the spatial “flips” experienced by astronauts in orbit[5].

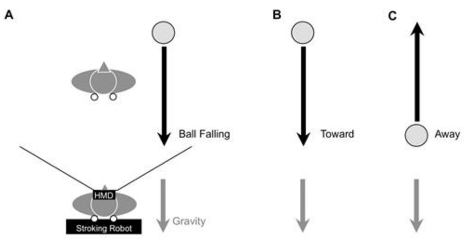

Fig 4: Experimental setup: students perceive “ball falling”

Coincidentally, De Stijl movement also tricks people’s visual vertical of gravity. Buildings on Earth are mostly built with hierarchy (or floors), but when there’s no or less “below” or “above” hierarchy, people’s cognition, habits, ... will inevitably change as well. The best example could be Dutch Neoplasticism, when Piet Mondrian’s artwork was displayed upside down for 75 years[6].

Fig 5: Schroder house

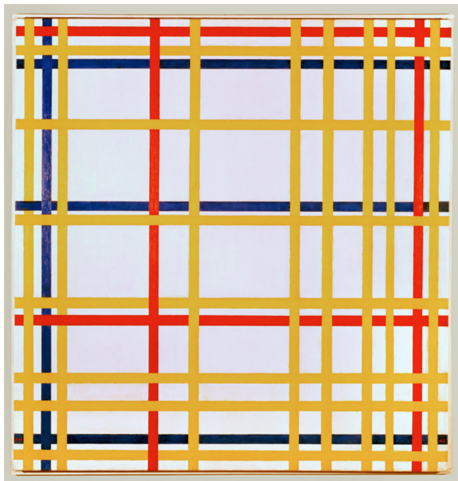

Fig 6: New York city (painting)

In conclusion, the design should not only deal with physical restraints, but also embrace intellectual and perception change in space age.

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5. Pfeiffer et al. (2016), Visual gravity contributes to subjective first-person perspective. https://academic.oup.com/nc/article/2016/1/niw006/2757126?login=false
6. BBC (2022). Piet Mondrian artwork displayed upside down for 75 years. https://www.bbc.com/news/entertainment-arts-63423811

1.2 Relevance

Prevent illusion and maintain well-being for Lunar habitants

In Gibson's "The Ecological Approach to Visual Perception", he argued that poor spatial perception design can lead to severe cognitive load, or even illusion[7]. While on earth, the effect of seasickness may provide a better description for this illusion. Seasickness occurs when the brain's "plumb line" and its "visual vertical" stop agreeing with each other. By aiming very far away, people regain visual anchor and thus the dizziness stopped.

While in moon EVA missions, low gravity worsen the situation of "plumb line", while the monotony environment provide few visual vertical, astronaut's motion may cause sickness, as stated in the report of Apollo 14[8]. The picture on the right also shows the perception on the moon is less clear whether there's a hill or a pit in the distance.

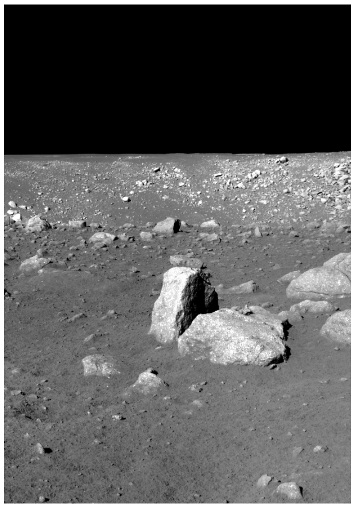

Fig 7: lunar surface

Improve spatial perception

Spatial research could improve design process by taking individual's perception into consideration, encourage design for specific purposes or functions as well as reduce cognitive load. For example design for dementia, or "Neuroarchitecture", enhancing cognitive performance in workspaces.

Fig 8: Design for dementia, Woonzorg

Fig 9: Salk Institute, Louis Kahn

Contribute to UN Sustainable Development Goals

The study of disorientation could help improve living environment for people who are experiencing cognitive decline.

When available space is very limited, visual anchor improvements could help building mental resilience among residents

3 GOOD HEALTH AND WELL-BEING

11 SUSTAINABLE CITIES AND COMMUNITIES

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7. Gibson, J.J. (2014). Ecological Approach To Visual Perception
8. NASA. (1971). Visual Optics in Space Flight. https://ntrs.nasa.gov/api/citations/19710024584/downloads/19710024584.pdf

1.3 Objectives and motivation

Space exploration has always been fascinating, yet the reality is very different from what we've seen from Sci-fi movies. In *2001: Space Odyssey (1968*), we are impressed by the spacecraft Discovery One, the Djinn chair, and the prediction of AI "HAL 9000" computer. The lasting impact goes beyond filmmaking, involved in Space Age Design, fashion industries and even the invention of iPad[9]. People's lifestyle had already been changed without going to space. However, in reality, the design for lunar habitat is heavily technology driven, yet is necessary, to meet the minimal requirement of survival on the moon. But to actually live there, humans need more than just the basics.

Architectural

Space colonization: Indicate a guideline for about lunar lifestyle more than just survival, and bring technological consciousness where space can be determined more than merely volume but also minds

Usually, we think of the Moon base is a life-supporting machine. But in this guideline, moon habitat is also about expanding human consciousness into the outer space. On the Moon, the technology keeping you alive, and the goal of designed space is to make our minds work together so that we feel connected to our environment, rather than scared of the "vacuum" outside.

Technical

Space-resilience: Embody cognition to spatial cues when designing lunar base, ISRU technology in Robot building and maintenance

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9. Medium (2018). 2001: A Space Odyssey is an experience that is beyond film. https://medium.com/swish/2001-aspaceodysseybeyondfilm-f5640fcb898d

1.4 Research and/or design questions

The main research question of this project is

How can architectural spatial design in extra terrestrial environment collaborate technology with perception, to embrace cognitive changes between movement and perception in maintaining mental well-being of future lunar habitants?

To answer this main research question, the following sub-questions will be answered:

1. Premise: Physical survival challenge
Design must be based on conscious research of physical ICE[10] conditions in constructing and inhabiting lunar bases with **ISRU**

2. Design: Sensing spaces
Based on visual cues and movement study, how can the **furniture, room, and lunar habitat** dealing with sensory deprivation and monotony due to loss of gravity vertical?

3. Sequel: Mind over matter
Between individuals, how can the built space and architectural expressions cope with **imbalance between privacy and social interaction**?

10. Isolated, Confined, and Extreme (ICE) challenge, developed by NASA
Oman C, M. et, al. (2006). The Role of Visual Cues in Microgravity Spatial Orientation. https://ntrs.nasa.gov/citations/20030068201

1.5 Scope

Location: Lunar South Pole

On sunlit peak point of rim at Shackleton Crater

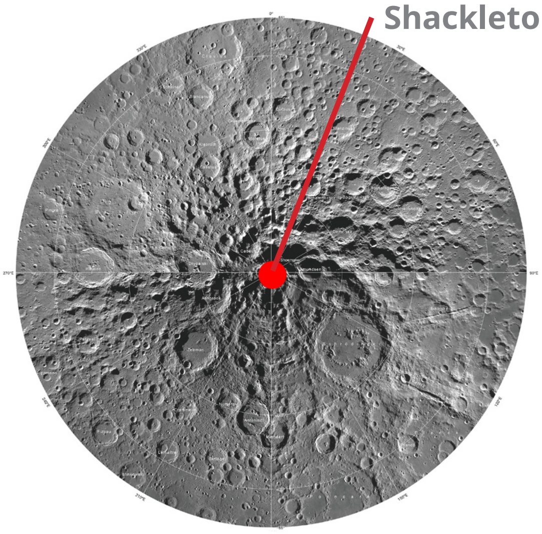


Fig 10: Lunar south pole

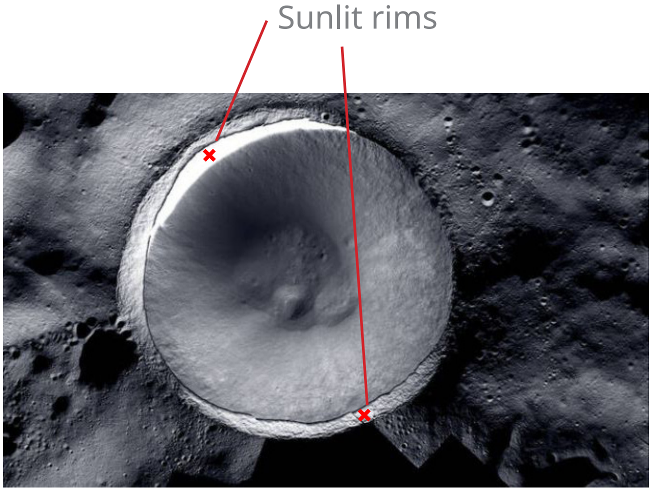


Fig 11: Shackleton Crater

The location choice is mainly resource driven:

Because of how the Moon tilts, the sun is always low on the horizon at the poles. Sunlight hits the rim of the crater but can never reach the bottom. At the Permanently Shadowed Regions (PSRs), water may exist because of the freezing temperature, along with other resources that are trapped by ice[11].

On the other hand, the perk received solar energy for 90% of the (earth) year. The advantage include solar energy, thermal radiation[12] and the ability to see the earth. This combination of resources is why NASA and also other space agencies see this specific crater as the best place to build the first permanent lunar city.

Core challenge

Apart from the universal challenge of life-support, the specific challenge for this peak location at the rim is 10% time at low degree (average -53°C) and cosmic radiation[13].

11, 12. NASA. (2022). Shackleton Crater's Illuminated Rim & Shadowed Interior. https://science.nasa.gov/resource/shackleton-craters-illuminated-rim-shadowed-interior/
13. Leonard, D. (2022). Leonard David's INSIDE OUTER SPACE. https://www.leonarddavid.com/artemis-iii-moon-landing-sites-identified/#:~:text=Credit%3A%20NASA,set%20foot%20on%20the%20Moon.

Context

After successful landings of multiple short-term lunar modules, this habitat is considered to be self-maintaining, lasting over a generation while developing to form their own space colonize culture. According to the space habitation plan by NASA, the context of this lunar base is settled in the 2080s, after humans have successfully harvest energy and material from PSRs of Shackleton Crater.

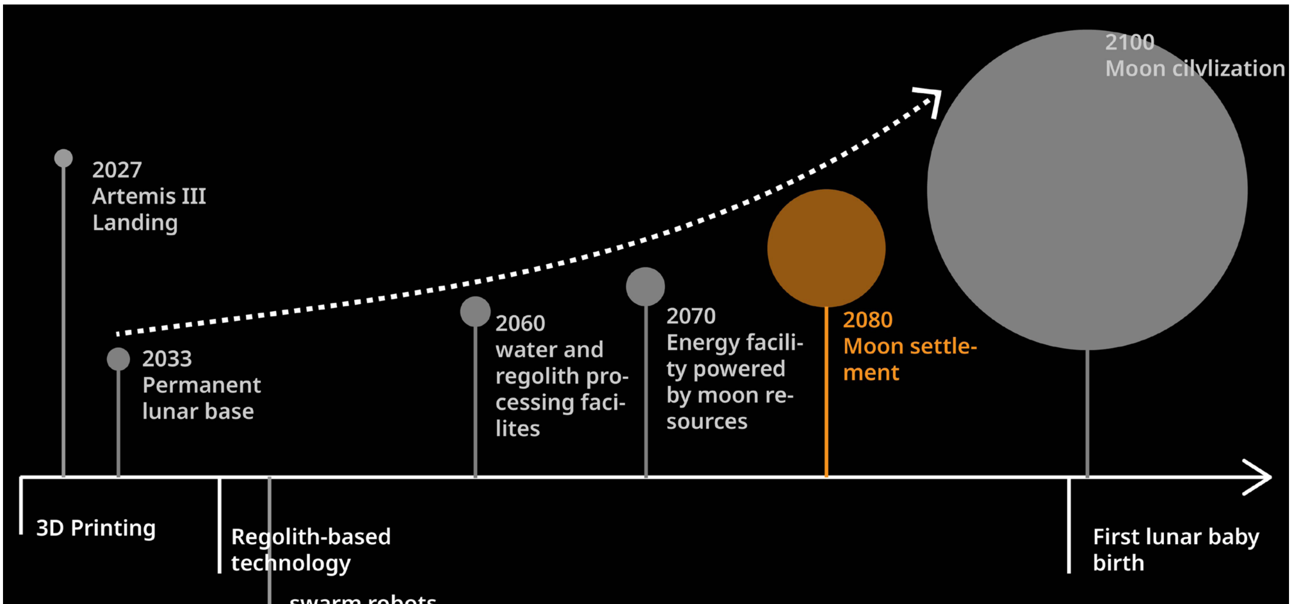


Fig 12: Project timeline

Target and overseeable field

There are three targets in construction of a moon base: **Survivable, sustainable and operational**[14], and this project is aimed at all three phases.

Survivable:
Include fundamental protection of 3D print in-situ elements, design for swarm robots and investigation pods for autonomy installation
Sustainable:
Accommodate researches in fabrication and preparation for future habitation
Operational:
Expand the habitat for long-term and self-sufficient living and working on the moon

Developed based on these three criteria, the design should be represented in micro scale in how human and robots' vision, movement, and human's perception can further influence the architectural expression in three phases.

14. ESA. 3D printing our way to the moon. https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/3D_printing_our_way_to_the_Moon

Part.2 Approach (how?)

2.1 Design methods

This research will employ a combination of literature study, case studies, workshops, as well as movement and visual studies to explore the logic behind human's physical receiving information and mental interpreting of space perception.

Spatial study

The study of **space perception** are carried out primarily developed from visual cues, but also combining information from other senses in hearing, touch, and balance[15], under subject area of "space perception".

To design without the "plumb line", the study of human response to difference geometry is also conducted. By simply ask the question "Does the shape of a room change how you feel?"[16], the researcher used **Virtual Reality (VR)** in experiment to prove geometry is a tool for the mind. This is helpful to determine rooms with different level of safety and functions.

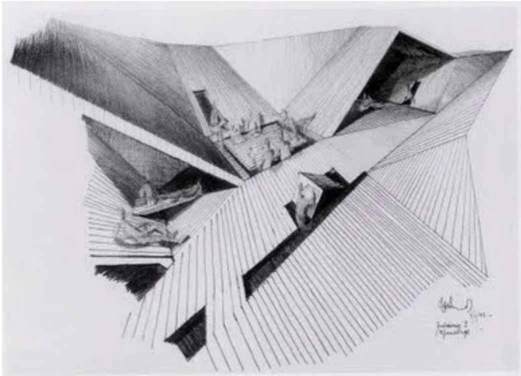
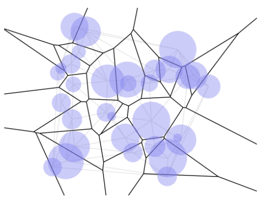


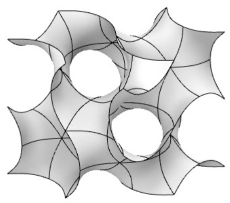
Fig 13: Oblique Function by Claude Parent and Paul Virilio

Moreover, the movement study is based on theory of *Oblique Function* by Claude Parent (architect) and Paul Virilio (philosopher). The study will examine the strength increase in muscular tension and compression in relation to human experience in different activities.

In realizing the goal of determine visual anchor and create visual and physical connection for different activities, multiple computation design will be used in the stage of designing, visualization and manufacturing.



Voronoi: will be used to determine the relationship between visual anchors based on how visual anchors are needed for different level of safety and activities



Gyroid: will be used to connect visual anchors, without defining the concept of "floor" (result of gravity vertical) but focus on the visual cues of entering other spaces.

Fig 14: Voronoi and Gyroid illustration

15. Science Direct. (n,d). Space Perception, definition based on: Nervous System Theory, 1972. https://www.sciencedirect.com/topics/social-sciences/space-perception.
16. Talmon, et.al. 2016. Affective response to architecture – investigating human reaction to spaces with different geometry. https://www.tandfonline.com/doi/full/10.1080/00038628.2016.1266597

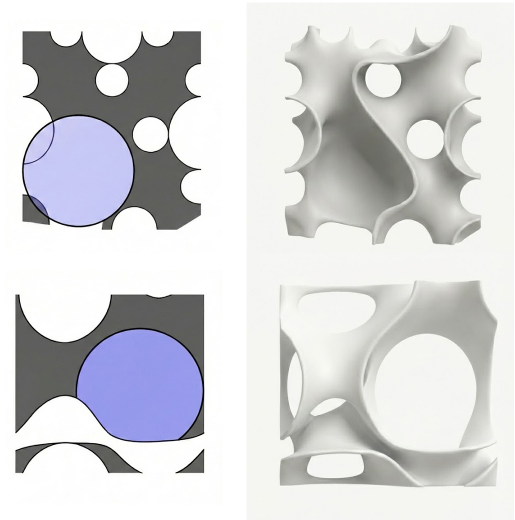


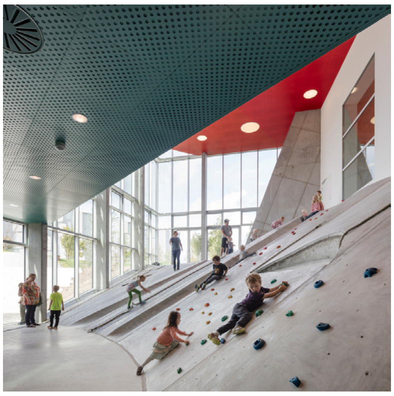
Fig 15: Voronoi and Gyroid combination

By combining Voronoi and Gyroid, the architectural representation can be both functionally and structurally logical as well as full of visual cues, achieving the goal of beyond survival to sustainable and operational living on the moon.

At the prototype production, computational design will also be used in the manufacturing automation, in both 3D-printing and milling architectural elements

Fig 16: Robot production workshop

Case studies



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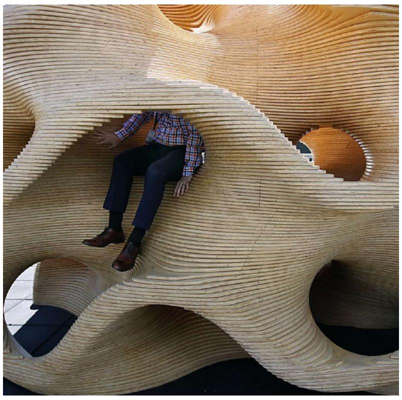
Ku.Be House
MVRDV + ADEPT
Frederiksberg

Instead of defining levels , architects use labyrinth, trap and net to move "upward"



18

Gyroid Climber
Exploratorium
San Francisco

Frictions and tensions occur due to the irregular surfaces, along with diverse light and geometry

Materialization

This project planned to use 3D printed lunar regolith as the main construction material using In-Situ Resource Utilization (ISRU) methods. Designed to utilize in-situ resources, it reduced the need for transporting construction materials long distances. Moreover, with the optimization of voronoi (closest neighbour) and gyroid shape (minimal distance), the design can use less material by using hollow structure.

Swarm robots are allocated in the construction phase of this project, each specialized in part of the construction[17]. Some collect dust, some are processors that melt and binding regolith, some are hardening regolith in situ[18], and others are printers.

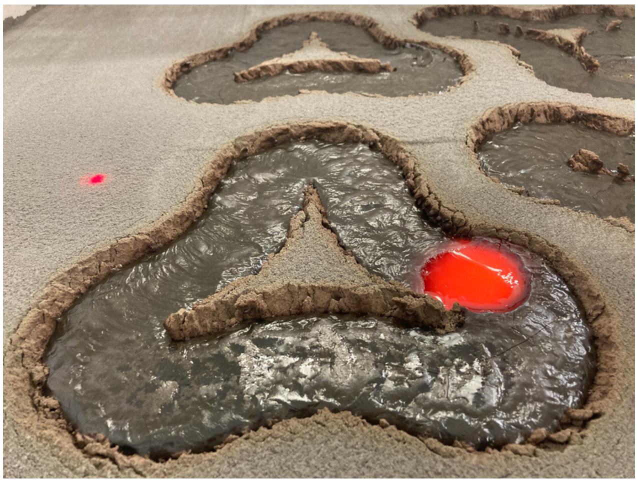


Fig 19: Laser melt and harden on regolith. ESA

17. Pereira, C., Neumann, A., Schubert, D., Zach, C., & Roeser, H. (2020). Lunar surface additive manufacturing: Development of a robotic system for in-situ fabrication. Proceedings of the 10th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS). https://elib.dlr.de/139976/1/Pereira%20-%20Lunar%20Surface%20Additive%20Manufacturing%20-%20iSairas2020.pdf
18. Agapkin, I. A., & Slyuta, E. N. (2025). A review of selective laser sintering/melting techniques for lunar construction. Acta Astronautica, 237, 315–325. https://doi.org/10.1016/J.ACTAASTRO.2025.08.047

2.2 Theoretical framework

Beyond the basic ‘survival’ in a temporary lunar base, this research is aimed to address the psychological and cognitive requirements of ‘living’ in an extreme environment. This framework is built upon the synthesis of neuroarchitecture, human centre design, and geometry optimization to maintain the well-being of future lunar inhabitants.

In the field of neuroarchitecture, this research will raise the situation of “missing plumb line” in low gravity situation and propose to design around this feature. According to Morfoisse et al., gravity is the fundamental anchor for the brain’s internal 3D map [19]. In low gravity, the human vestibular system becomes disordered, leading to visual misjudgements of distance and orientation. Then the research raised the concept of “visual gravity”, as evidence proved that humans “see” gravity in their environment[20]. This project uses these neuroarchitectural insights to design “visual anchors” that compensate for the lack of a physical plumb line.

Human centred design acts as the basic logic behind defining visual anchors. By focusing on understanding human’s needs, behaviours and reaction to contexts, the research will analysis the collaboration effort between body movement and perception in shaping spaces in low gravity. This project will build on the awareness of lunar habitats’ lives, challenges and relationships, with iterative process that continuously test and gather feedback from simulated experiences.

Geometry optimization is the framework that put theory to real-life. It includes computational design and Autonomous Materialization through In-Situ Resource Utilization (ISRU). Optimized by neighbouring and shortest distance logic, the project can realize both structural and neural optimism. Last but not least, the use of 3d printing lunar regolith provides the necessary radiation and thermal shielding, allowing the internal “neuro-designed” volume to become space resilience within the lunar surface

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19. Morfoisse, T. et, al. (2024). Modality-Independent Effect of Gravity in Shaping the Internal Representation of 3D Space for Visual and Haptic Object Perception
20. Pfeiffer et al. (2016), Visual gravity contributes to subjective first-person perspective

Reference

Agapkin, I. A., & Slyuta, E. N. (2025). A review of selective laser sintering/melting techniques for lunar construction. Acta Astronautica, 237, 315–325. https://doi.org/10.1016/J.ACTAASTRO.2025.08.047

Balashova, G. (1980). Topography design for the Mir space station. http://kvadratinterwoven.com/out-of-this-world-the-space-age-designs-of-galina-balashova
BBC (2022). Piet Mondrian artwork displayed upside down for 75 years. https://www.bbc.com/news/entertainment-arts-63423811

ESA. 3D printing our way to the moon. https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/3D_printing_our_way_to_the_Moon

Gibson, J.J. (2014). Ecological Approach To Visual Perception

Leonard, D. (2022). Leonard David's INSIDE OUTER SPACE. https://www.leonarddavid.com/artemis-iii-moon-landing-sites-identified/#:~:text=Credit%3A%20NASA,set%20foot%20on%20the%20Moon.

Medium (2018). 2001: A Space Odyssey is an experience that is beyond film. https://medium.com/swish/2001-aspaceodysseybeyondfilm-f5640fcb898d

MIT Media Lab (2024). Moony Tubes.

Morfoisse, T. et, al. (2024). Modality-Independent Effect of Gravity in Shaping the Internal Representation of 3D Space for Visual and Haptic Object Perception https://www.jneurosci.org/content/jneuro/44/13/e2457202023.full.pdf

NASA. (1971). Visual Optics in Space Flight. https://ntrs.nasa.gov/api/citations/19710024584/downloads/19710024584.pdf

NASA. (2022). Shackleton Crater's Illuminated Rim & Shadowed Interior. https://science.nasa.gov/resource/shackleton-craters-illuminated-rim-shadowed-interior/

Oman C, M. et, al. (2006). The Role of Visual Cues in Microgravity Spatial Orientation. https://ntrs.nasa.gov/citations/20030068201

Pereira, C., Neumann, A., Schubert, D., Zach, C., & Roeser, H. (2020). Lunar surface additive manufacturing: Development of a robotic system for in-situ fabrication. Proceedings of the 10th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS). https://elib.dlr.de/139976/1/Pereira%20-%20Lunar%20Surface%20Additive%20Manufacturing%20-%20iSairas2020.pdf

Pfeiffer et al. (2016), Visual gravity contributes to subjective first-person perspective. https://academic.oup.com/nc/article/2016/1/niw006/2757126?login=false

Science Direct. (n,d). Space Perception, definition based on: Nervous System Theory, 1972. https://www.sciencedirect.com/topics/social-sciences/space-perception.

Reference

Talmon, et.al. 2016. Affective response to architecture – investigating human reaction to spaces with different geometry. https://www.tandfonline.com/doi/full/10.1080/00038628.2016.1266597

Figures:

Fig 1: Orion: crew capsule. https://www.esa.int/ESA_Multimedia/Images/2022/11/Orion_crew_capsule

Fig 2: Mir. http://kvadratinterwoven.com/out-of-this-world-the-space-age-designs-of-galina-balashova

Fig 3: Reduced Gravity Walking Simulator - NASA 1963. https://www.netflix.com/nl/title/81466983

Fig 4: Experimental setup: students perceive "ball falling" https://scispace.com/pdf/visual-gravity-contributes-to-subjective-first-person 23fyqjpy0e.pdf#:~:text=The%20FBI%20consists%20of%20visuo-tactile%20stroking-induced%20changes,(2012);%20Ehrsson%20(2012);%20Pfeiffer%20(2015)%20for%20reviews%5D.

Fig 5: Schroder house. https://www.archdaily.com/99698/ad-classics-rietveld-schroder-house-gerrit-rietveld?ad_medium=gallery

Fig 6: New York city (painting). https://www.newyorker.com/culture/cultural-comment/the-case-of-the-upside-down-mondrian

Fig 7: lunar surface. https://www.scmp.com/news/china/policies-politics/article/1908638/china-releases-new-pictures-showing-stunning-details

Fig 8: Design for dementia, Woonzorg.

Fig 9: Salk Institute, Louis Kahn. https://www.gsd.harvard.edu/2021/07/small-institutions-on-rediscovering-the-emotional-conditions-of-architecture/

Fig 10: Lunar south pole.

Fig 11: Shackleton Crater. https://www.newscientist.com/article/2442113-should-we-put-a-frozen-backup-of-earths-life-on-the-moon/

Fig 12: Project timeline. Anthor's own

Fig 13: Oblique Function by Claude Parent and Paul Virilio. https://www.archdaily.com/1007880/claude-parent-architectural-fictions-exhibition

Fig 14: Voronoi and Gyroid illustration. Anthor's own

Fig 15: Voronoi and Gyroid combination. Anthor's own

Fig 16: Robot production workshop. Anthor's own

Fig 17: Ku.Be House. https://www.mvrdv.com/projects/50/kube-house-of-culture-and-movement

Fig 18: Gyroid Climber. https://mathtourist.blogspot.com/2015/09/gyroid-climber.html

Fig 19: Laser melt and harden on regolith. ESA. https://www.esa.int/ESA_Multimedia/Images/2023/10/Melting_a_triangular_pattern_in_regolith