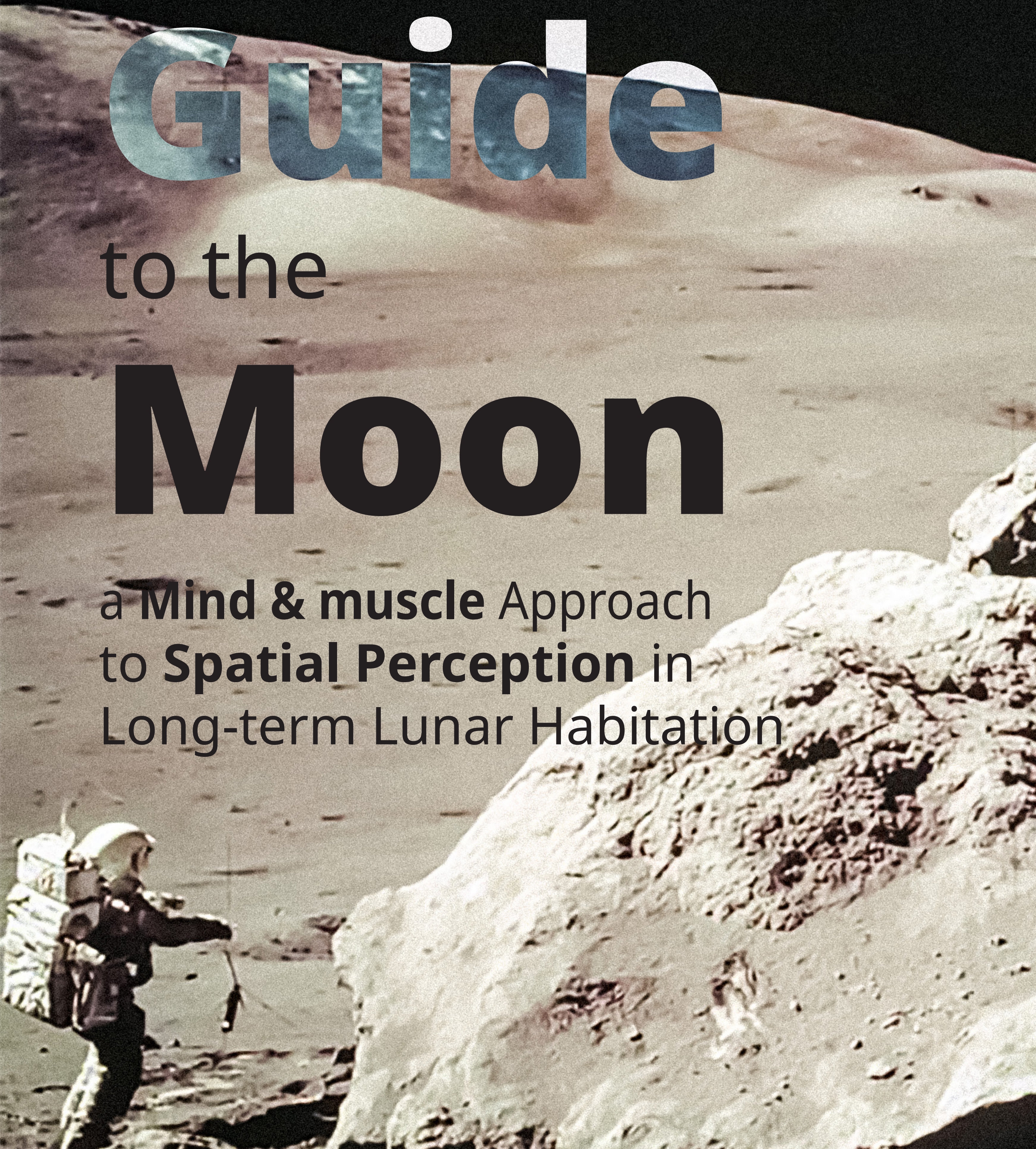
The Hitchhiker's Guide to the Moon

a **Mind & muscle** Approach to **Spatial Perception** in Long-term Lunar Habitation



The Hitchhiker’s Guide to the Moon
A Mind & muscle Approach to Spatial Perception in Long-term Lunar Habitation

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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 mind-and-muscle framework for spatial perception in 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 Point Charge (influence of charge strength) and Gyroid (minimal distance) logics, which optimizes both structural integrity and sensory complexity. Finally, the structural realization of this environment employs 3D regolith printing with In-Situ Resource Utilization (ISRU).

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:
Low-gravity, Visual cues, Spatial perception, Human-centred design, 3D printing and milling, In-Situ Resource Utilization (ISRU)

INDEX

1.0 BACKGROUND

1.1 Context

From ‘surviving’ to ‘living’: Now we landed on the Moon, then what?

Space engineering determines how to ‘survive’ in outer space. When it comes to habitation, would it be 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?

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 (Balashova, 1980).

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

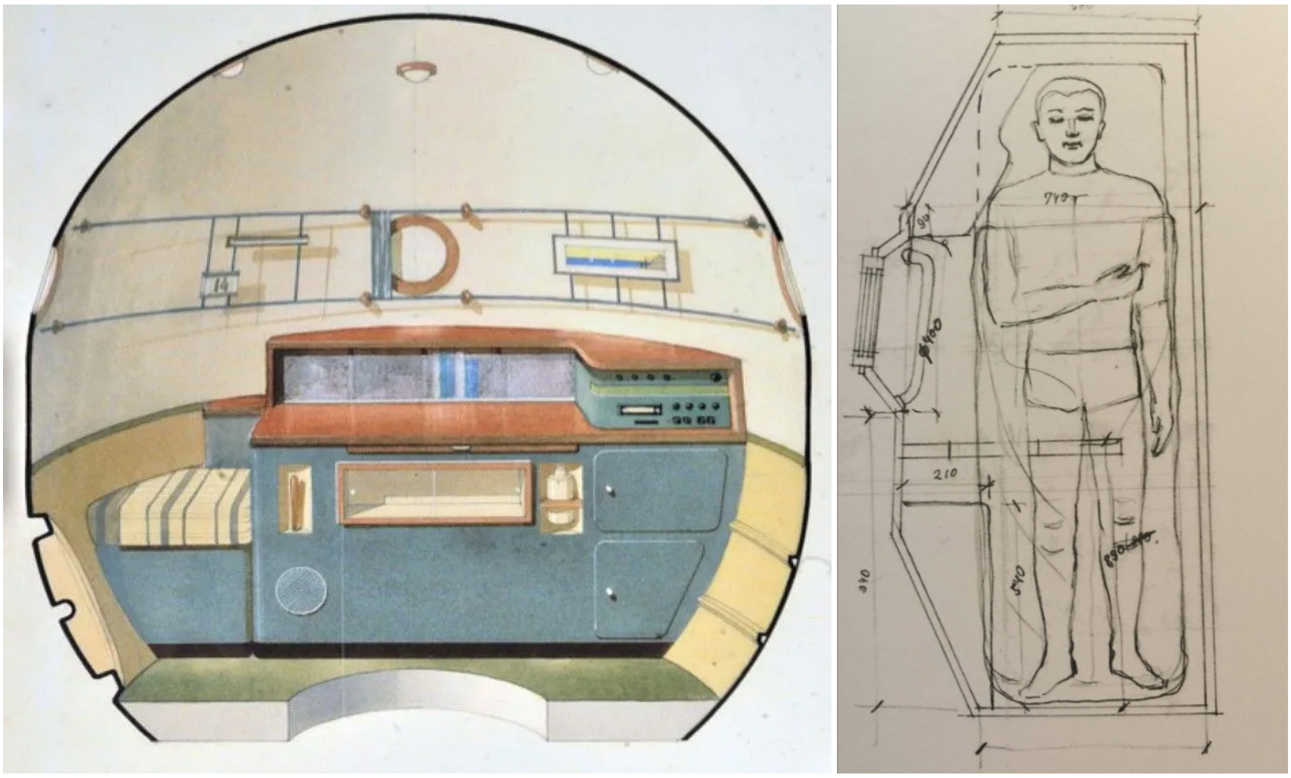


Fig.1.1 Sleeping pod. Galina Balashova

2.0 PROBLEM STATEMENT

2.1 Main problem

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

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 (2024) 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’ (Morfoisse et al., 2024). 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 (NASA, 1971). Later research indicates that brain often defaults to mind and muscle vector: Down is simply measured by eyes or wherever your feet are pointing, regardless of the actual slope.

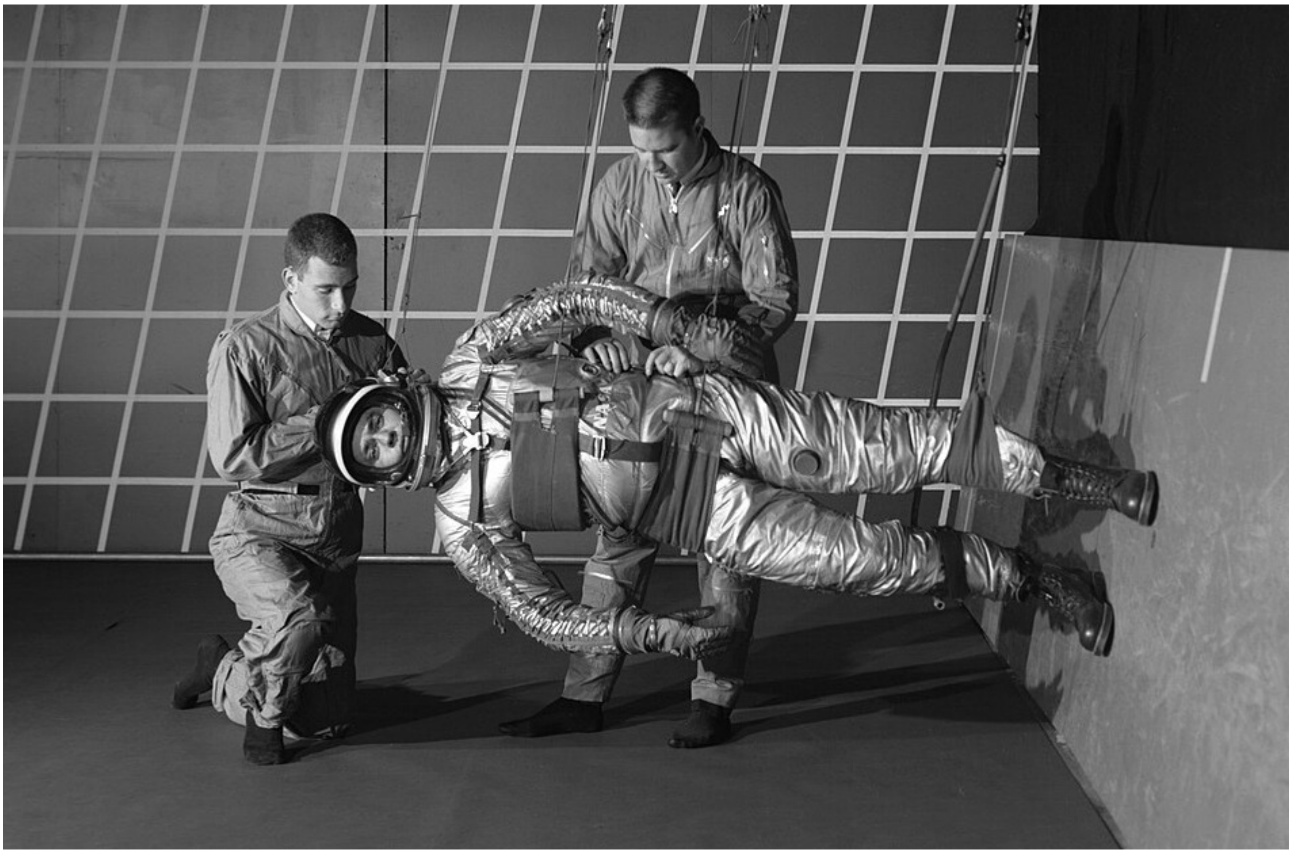


Fig 1.2: NASA testing moon gravity cognition, in a horizontal way

3.0 OBJECTIVE

3.1 General Objective

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 (Medium, 2018). 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

4.0 RESEARCH QUESTIONS

4.1 Main Research Question

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?

4.2 Sub Research Questions

1. Premise: Physical survival challenge

Design must be based on conscious research of physical ICE conditions in constructing and inhabiting lunar bases with ISRU (Oman C, M. et al., 2006)

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?

5.0 APPROACH & METHODOLOGIES

5.1 Scope

Location: Lunar South Pole. On sunlit peak point of rim at 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 (NASA, 2022).

On the other hand, the perk received solar energy for 90% of the (earth) year. The advantage include solar energy, thermal radiation and the ability to see the earth (NASA, 2022). 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.

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 (Leonard, 2022).

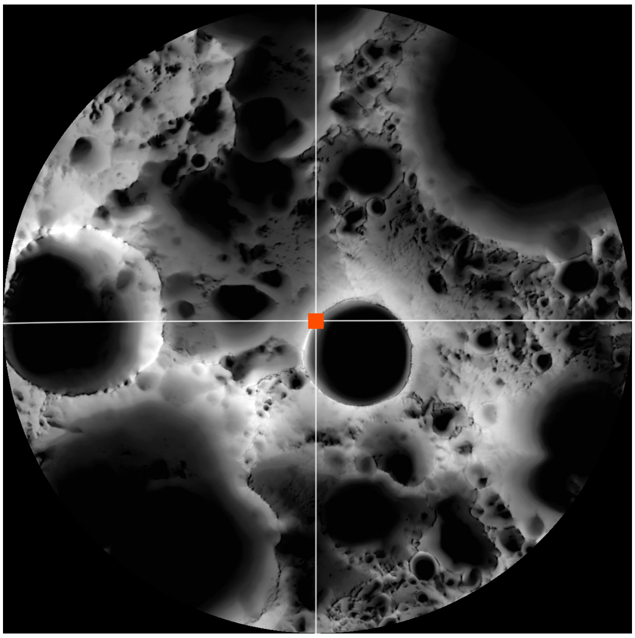


Fig 5.1: Lunar south pole

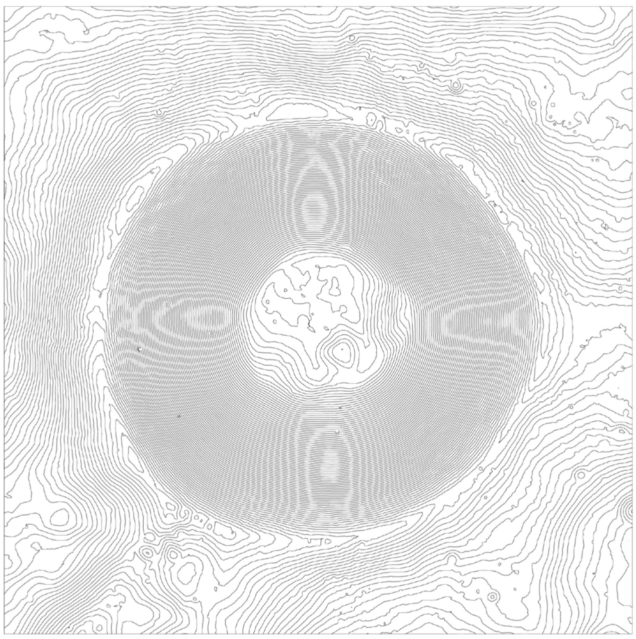


Fig 5.2: Shackleton Crater

Timeline: Completion in 2080s

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.

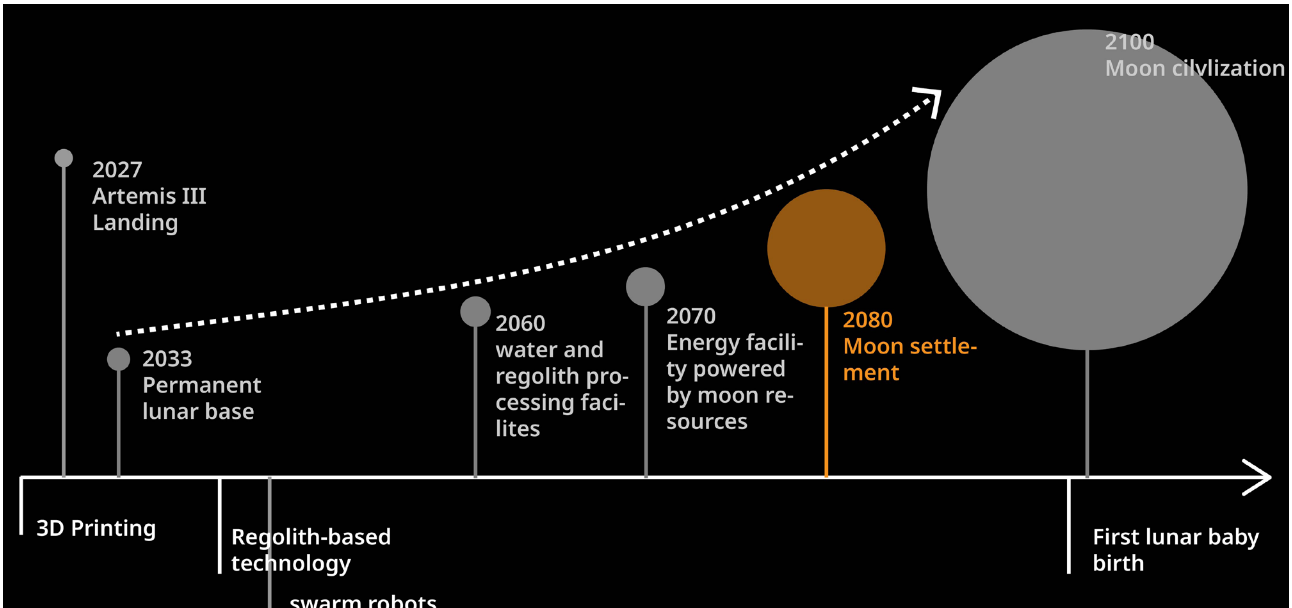


Fig 5.3: Project timeline

Target and overseeable field

There are three targets in construction of a moon base: Survivable, sustainable and operational(ESA, 2019), 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

5.2 Research Design

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 (Pfeiffer et al., 2016).

Threfore, 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.

5.2.1 Muscular perception in experiments

Experiments show the essence behind moonwalk is body's adaptation to 1/6G lunar gravity. The sense of space and 'down' is reclaimed by paying attention to keep body steady, as you need to know how you are going to fall based on the surface you touch.

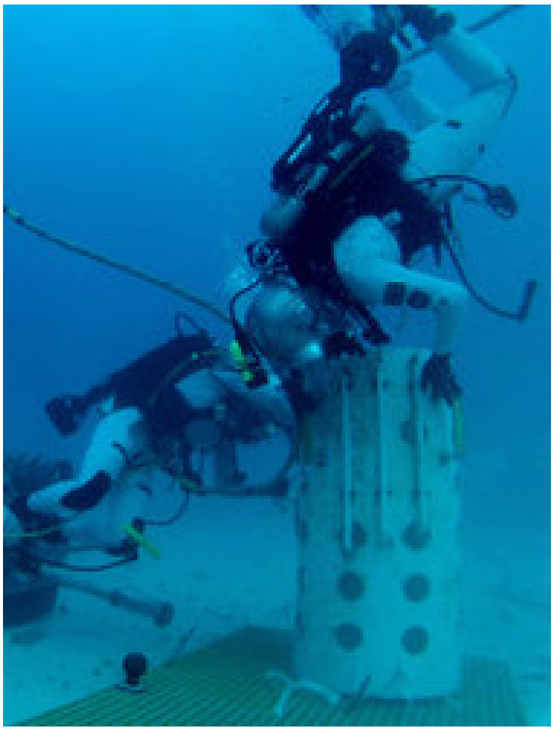


Fig 5.4: Moonwalk practice

Fig 5.5: Moonwalk by Apollo 17 astronaut

5.2.2 Muscular perception in architectural theory

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

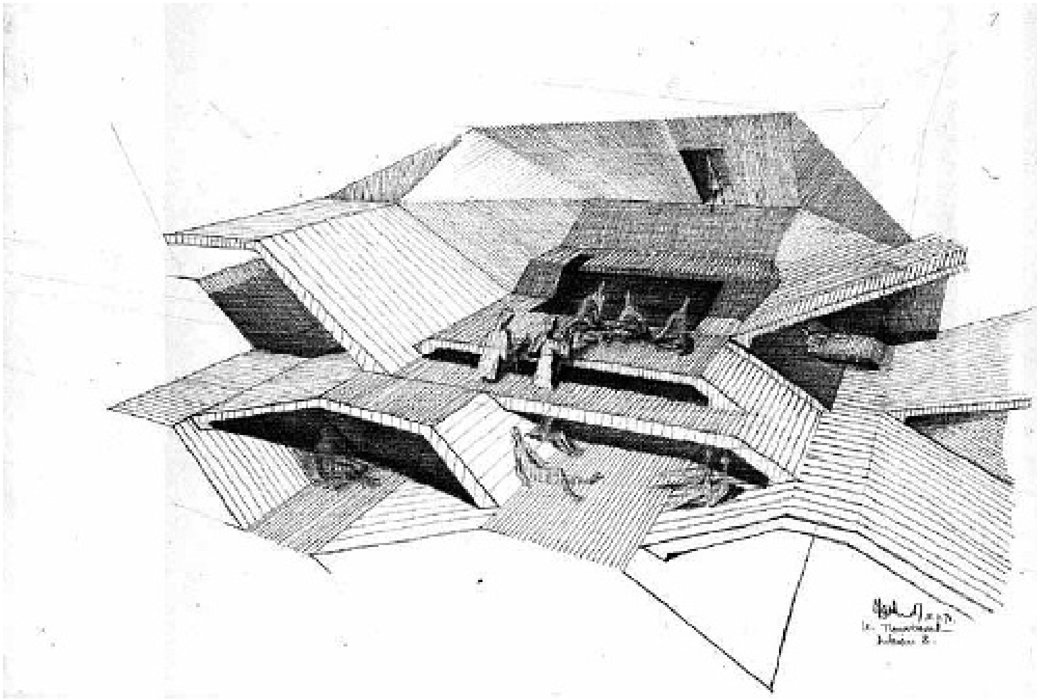


Fig 5.6: Oblique Function by Claude Parent and Paul Virilio

5.2.3 Visual perception in psychological research

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, under subject area of “space perception”.

To design without the “plumb line”, the study of human response to difference geometry is also conducted. In the research of Talmon, et.al. (2016), by simply ask the question “Does the shape of a room change how you feel?”, 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.

Gibson (1950; 1966; 2014) also points out in ecological field that, the meaning of vision is that we don’t just see geometry, we see what an object affords us. In his theory, visions can be translated in abstract patterns of *Fields of affordance*, which then is helpful in abstracting the geometry of vision that move beyond the unmesurable sight seen to sight encountered.

5.2.4 Visual perception in architectural theory

Similar approaches are already taken place in architectural field, but without mentioning the name of 'spatial perception'. Dated back to Bauhaus in 1930, the original diagram emerged from Bayer's work and his interest in psychology and ergonomics. He argued that the traditional "picture on a wall" approach ignored the natural range of human sight. His theory and later 1935 exhibition shifted the definition of an exhibition from a collection of objects to a designed experience. By acknowledging the 180 vertical and 360 horizontal potential, he proposed that display surfaces should be angled to meet the eye perpendicularly, regardless of where they are placed in a room.

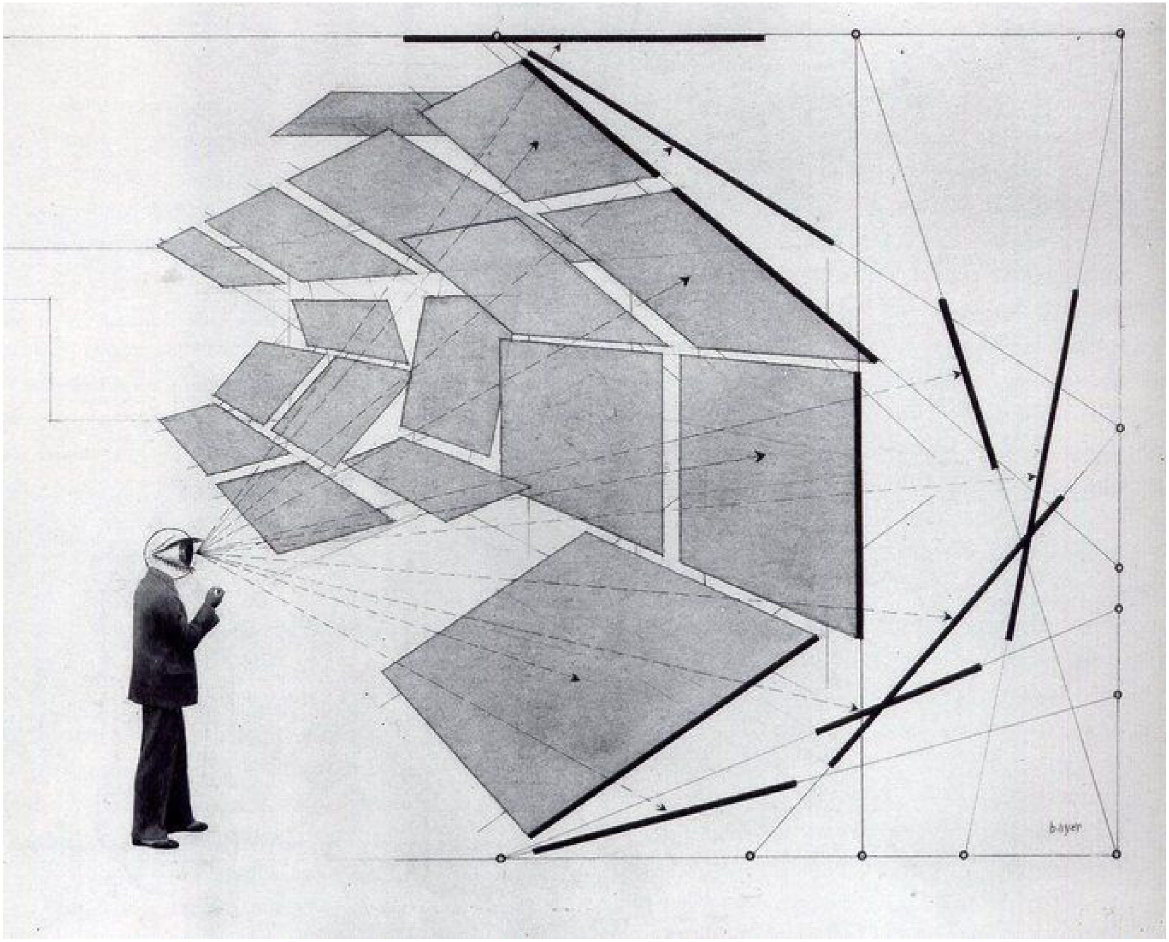
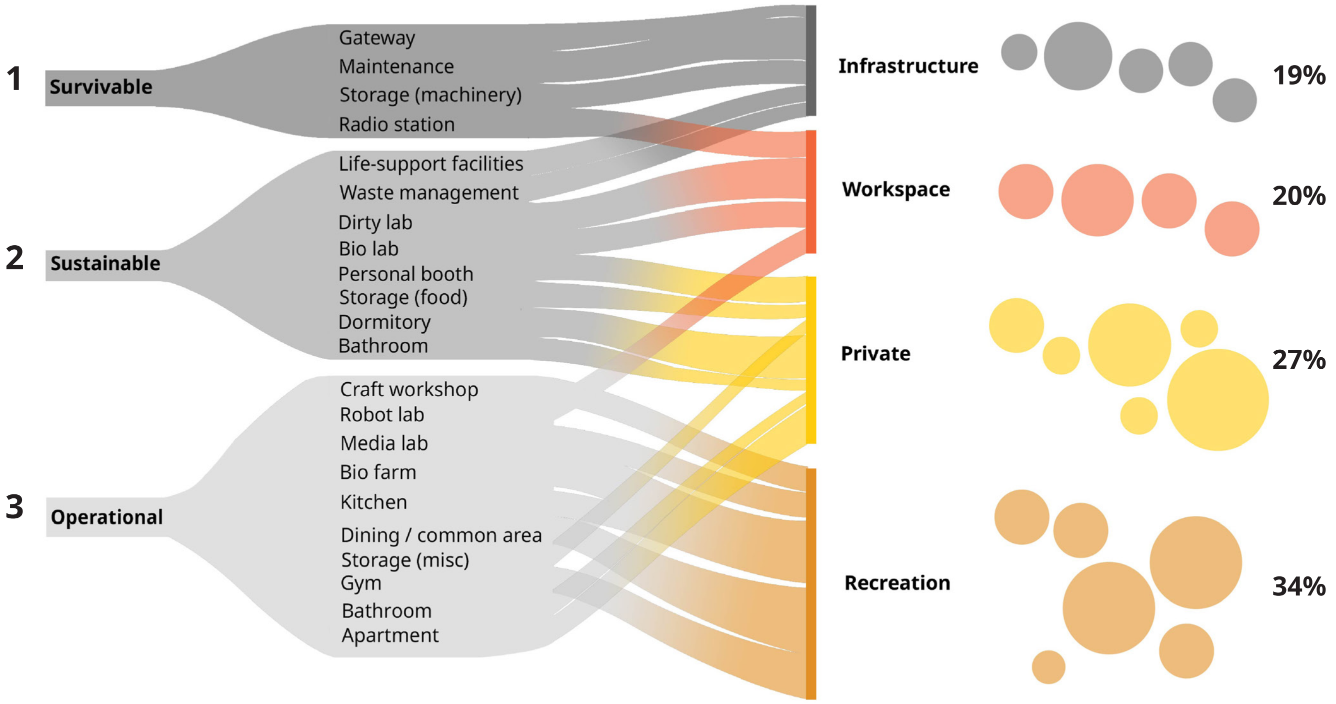


Fig 5.7: Diagram of the Extended Field of Vision, Herbert Bayer (1930)

5.3 Spatial Design

5.3.1 Programmes

The visualization Categorize the expansion of a moon base: Survivable, sustainable and operational. Each phase then form spaces to required functionality required by ESA.

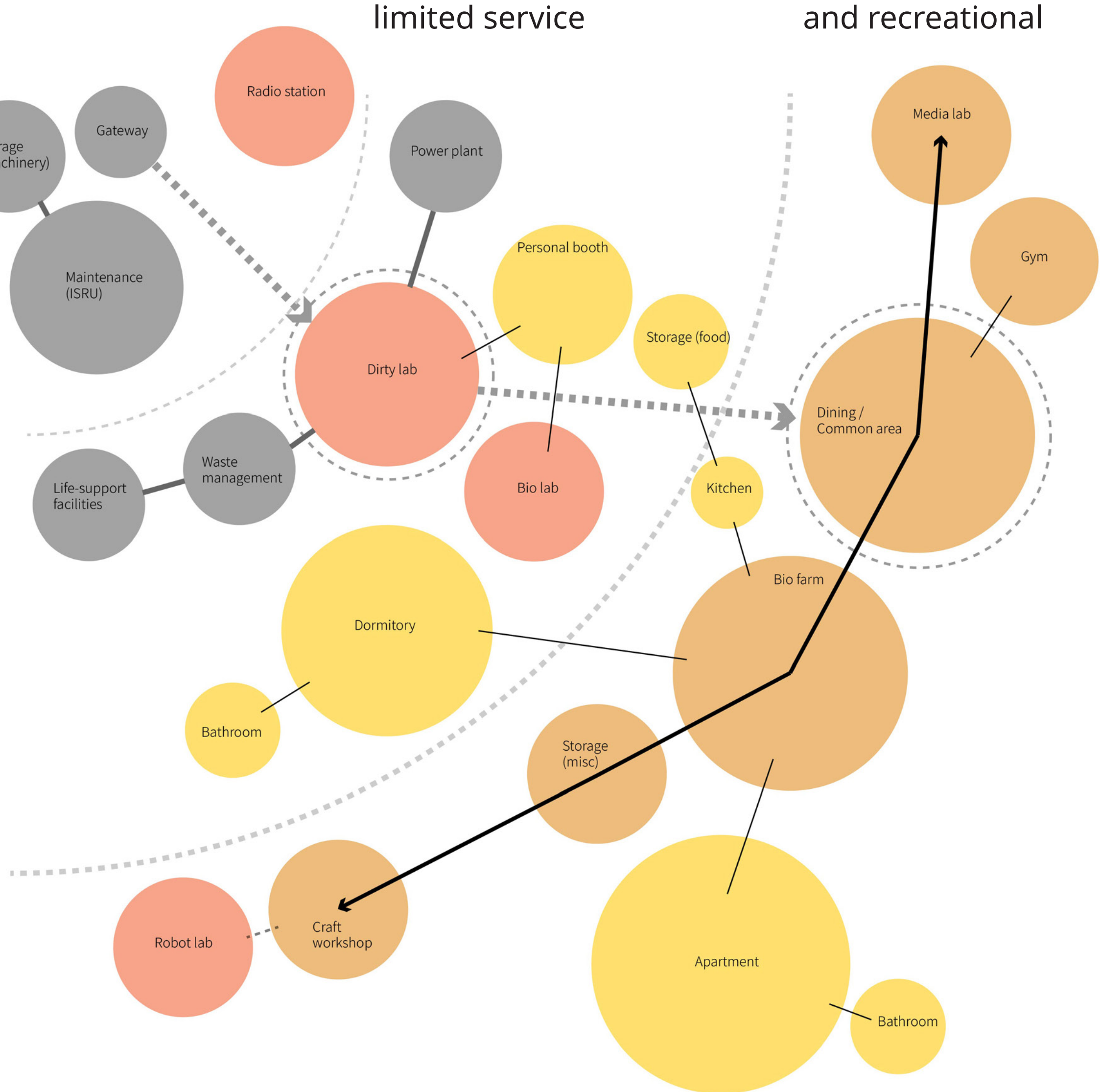


Program expansion

1. Survival
Fundamental and rigid

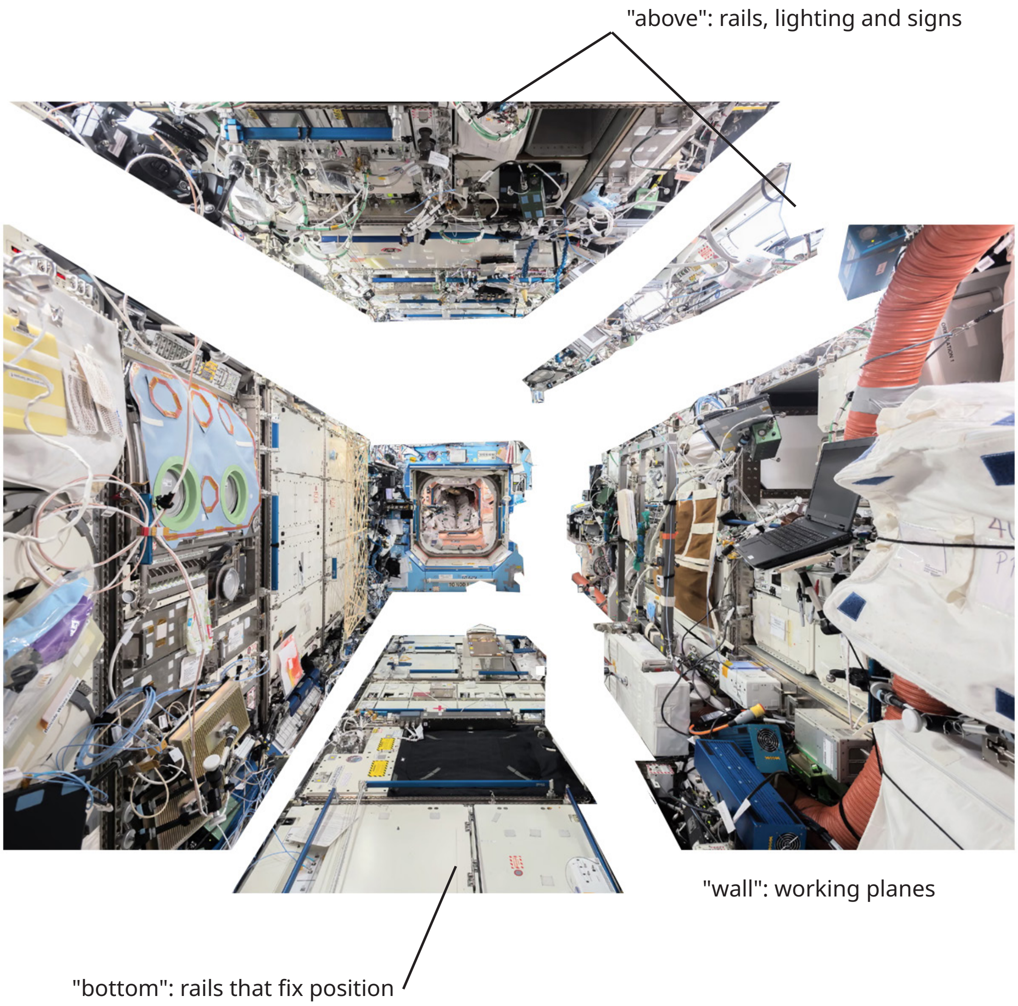
2. Sustainable
Resource first,
limited service

3. Operational
More flexible
and recreational



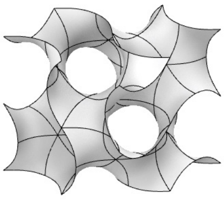
5.3.2 Spatial attractors

By analysing current designs and changes in space station in an archaeological way, we can get an impression of what are contributing to muscular perception and to visual perception (Walsh, 2021).



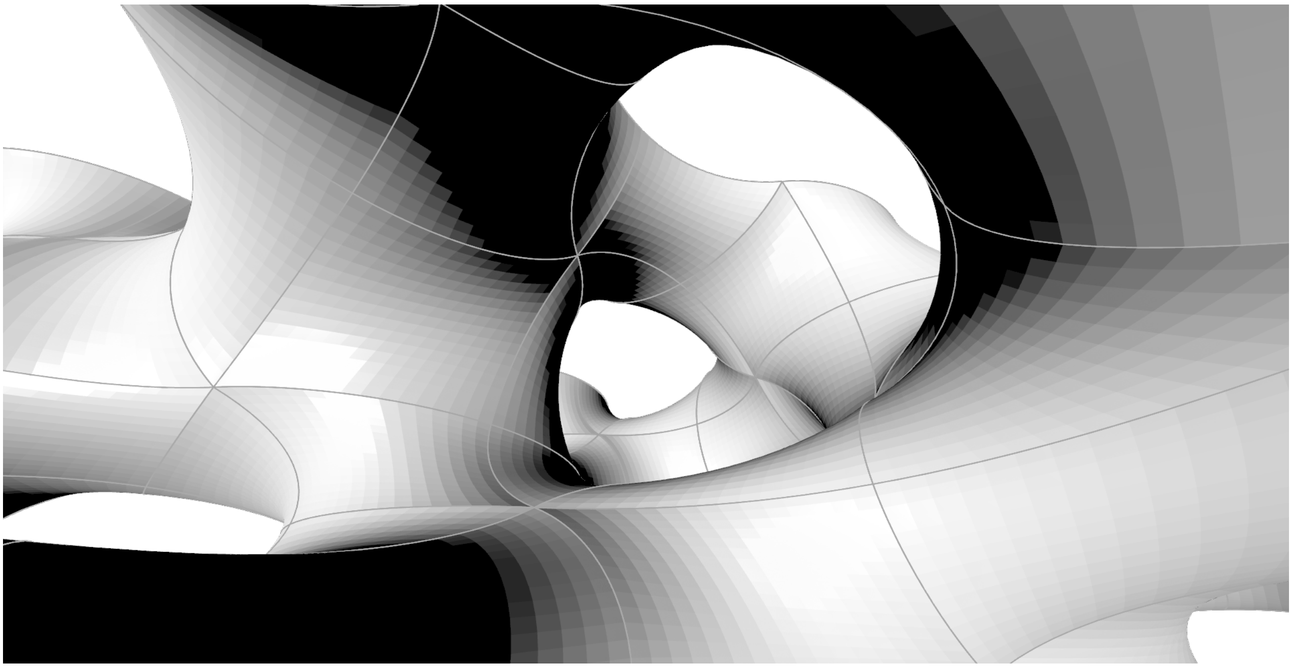
5.4 Computational Approach

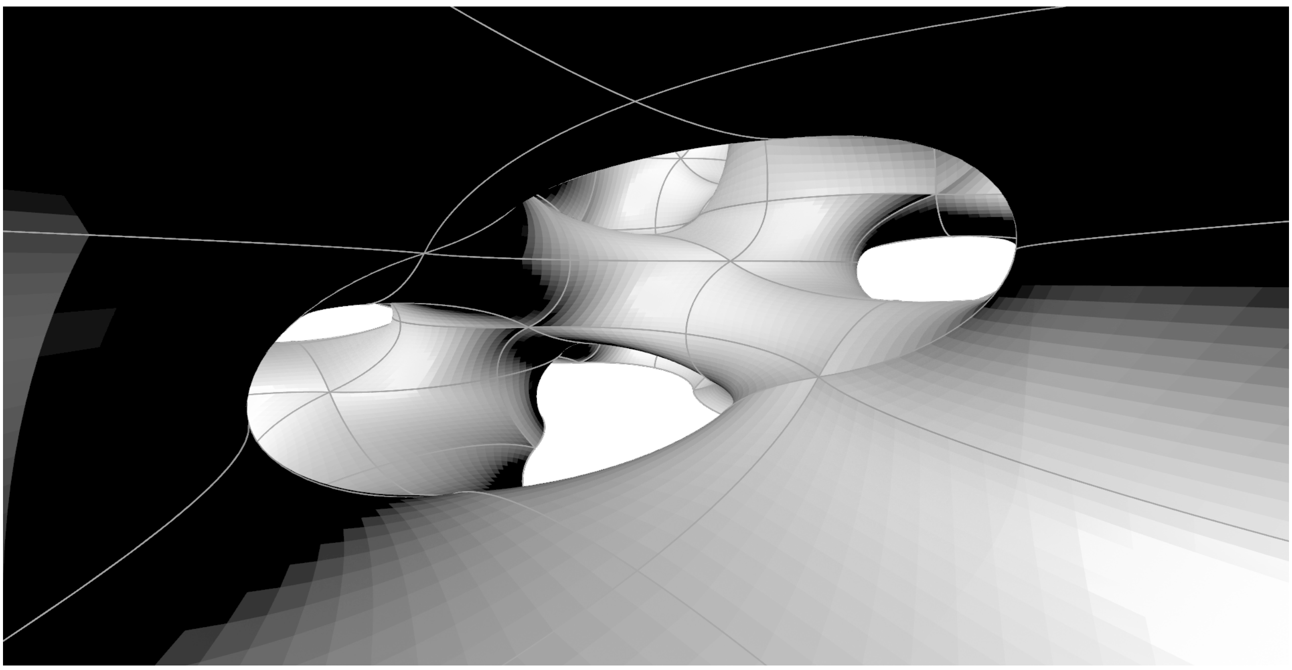
In realizing the goal of determine visual anchor and create visual and physical connection for different activities, multiple computation design will be used in the stage of designing, visualization and manufacturing.



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.

First impressions





5.5 Case Studies

Gyroid Climber San Francisco Exploratorium

The structure is based on a "gyroid," a complex infinitely connected triply periodic minimal surface that contains no straight lines. This creates a series of smooth, curving tunnels and surfaces that look like an optical illusion come to life. Frictions and tensions occur due to the irregular surfaces, along with diverse light and geometry

Ku.Be House Frederiksberg

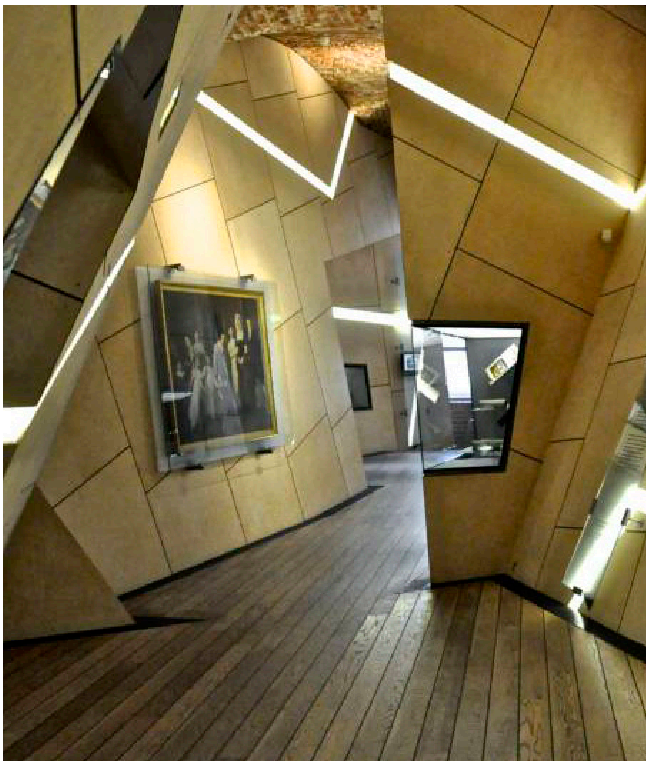
MVRDV + ADEPT

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

Jewish Museum Berlin & Danmark

Daniel Libeskind

In standard architecture, we expect 90-degree angles. Libeskind systematically eliminates them. Every room and corridor is composed of sharp, “stabbing” corners or wide, “stretching” walls. This forces the eye to constantly adjust to unpredictable perspectives.

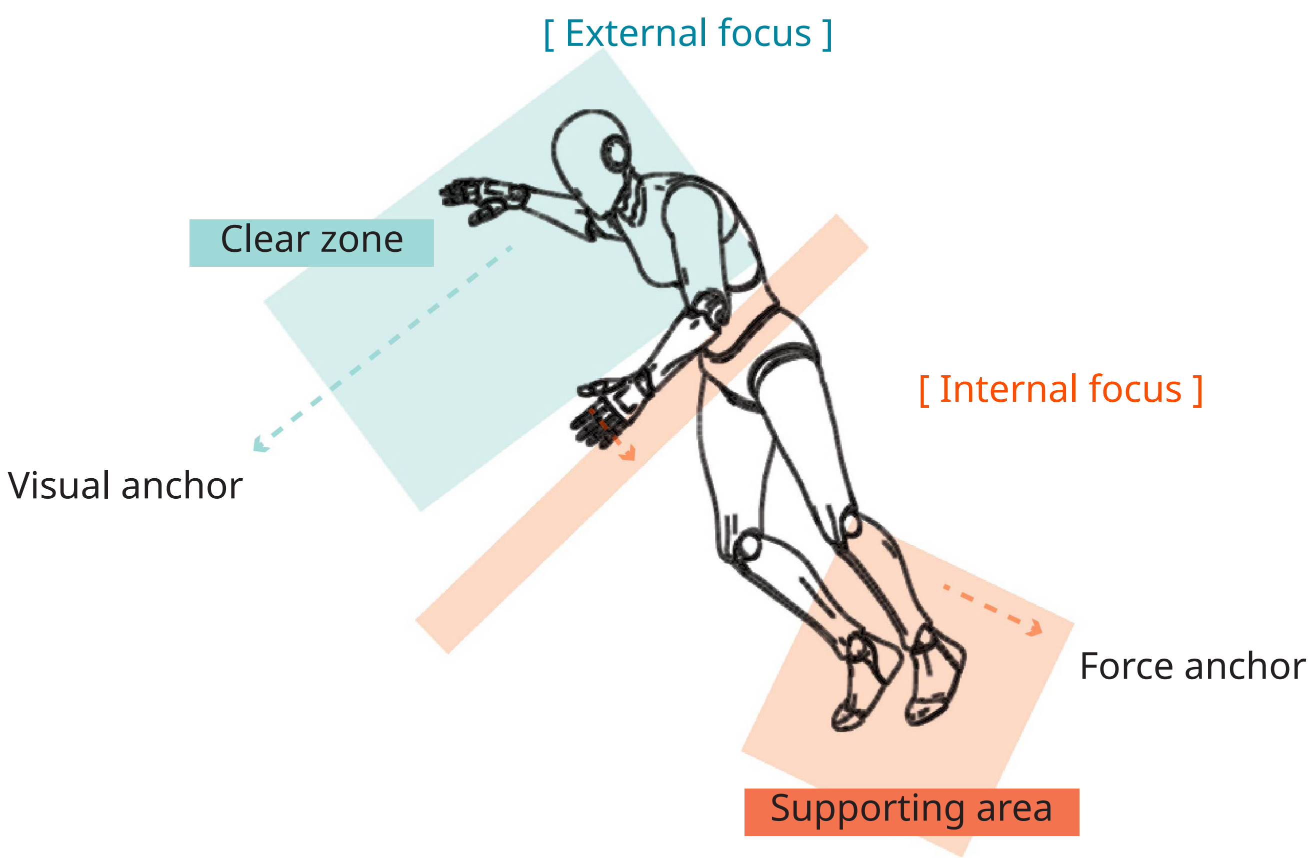


6.0 DESIGN

6.1 Interpretation of anchors

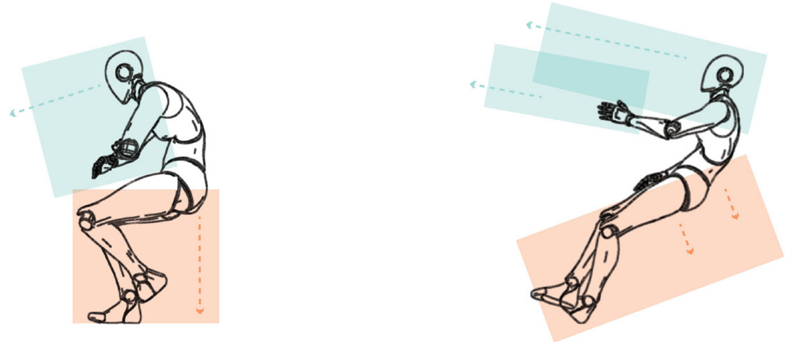
People react differently according to ambient environment, but in an opposite way, the space can be defined for convenience so that users can quickly understand the different ambient by experiencing themselves in certain mode of vision and body position. Before defining the actual boundary and geometry, the correspond body position is analysed and divided into multiple anchors and attractors.

External focus:	Reception, interaction of space and outcome
Internal focus:	Pay attention to keep body steady
Clear Zone:	Visually isovist-clear zone that allows interaction
Supporting area:	Physically connecting area for muscle respond
Visual anchor:	Horizontal extension of vision
Force anchor:	Perpendicular force applied to surface

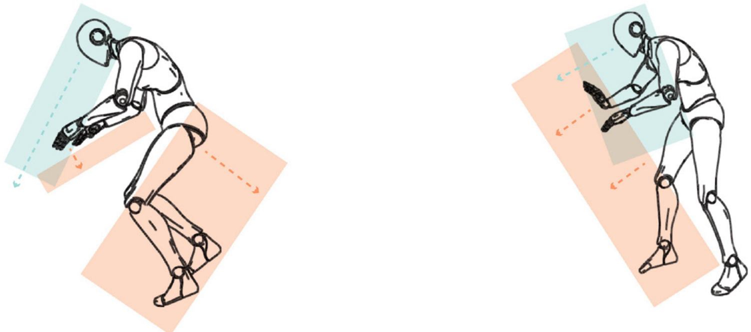


6.2 List of analysed movements

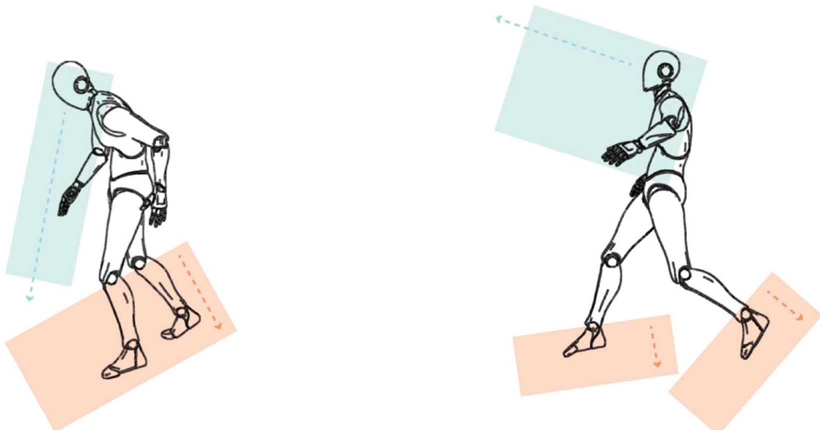
Chatting



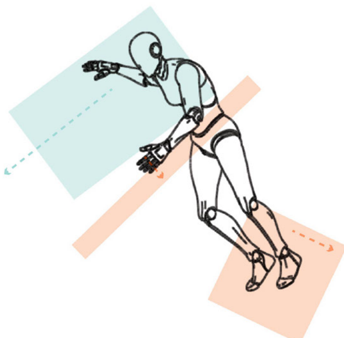
Operating



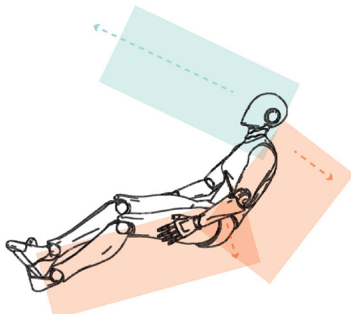
Looping



Exploring



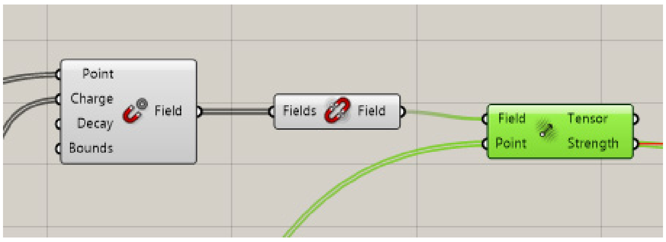
Lying

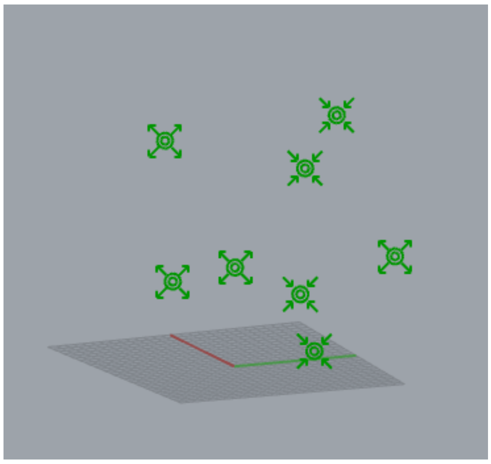


6.3 Computational translation

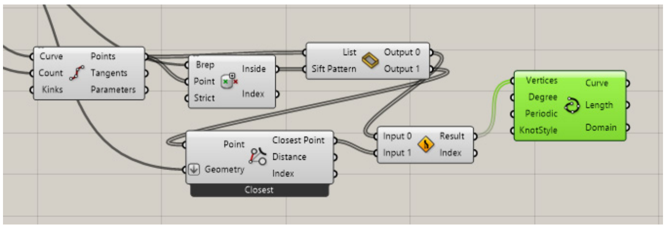
This approach translates from non-standard impressions to measured attractors and vectors, contributing rooms with individual gravities.

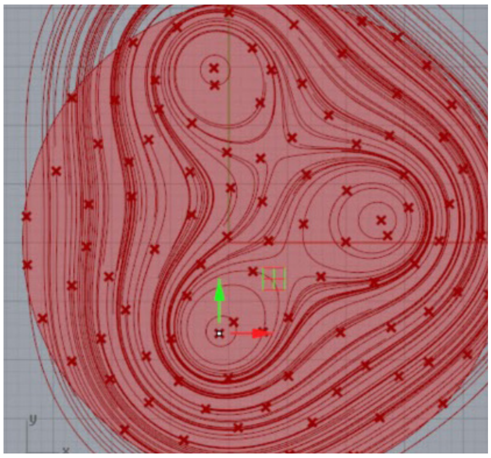
1. determine force charge points



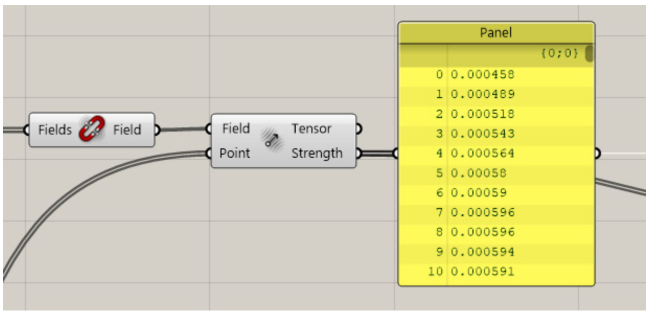


2. pull force to visual leading lines

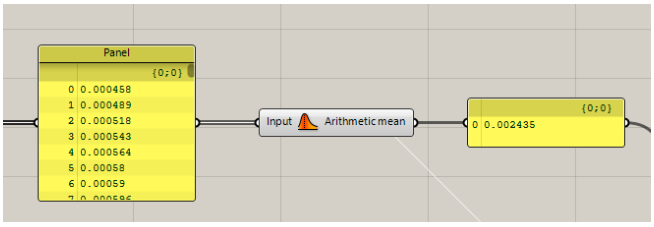




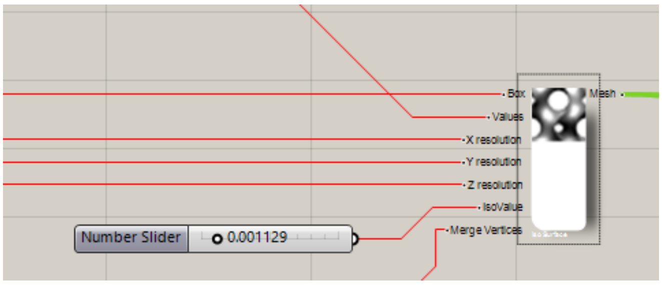
3. List anchors

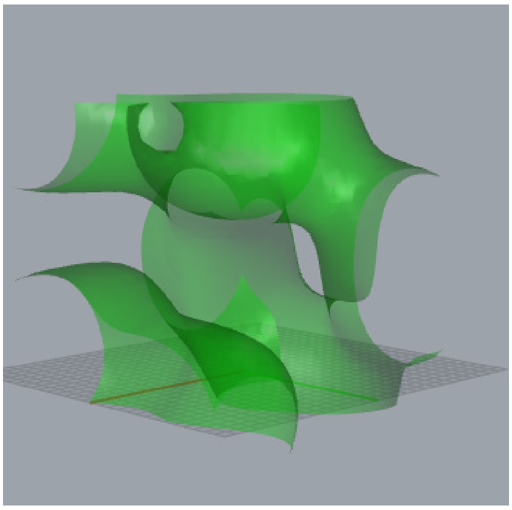


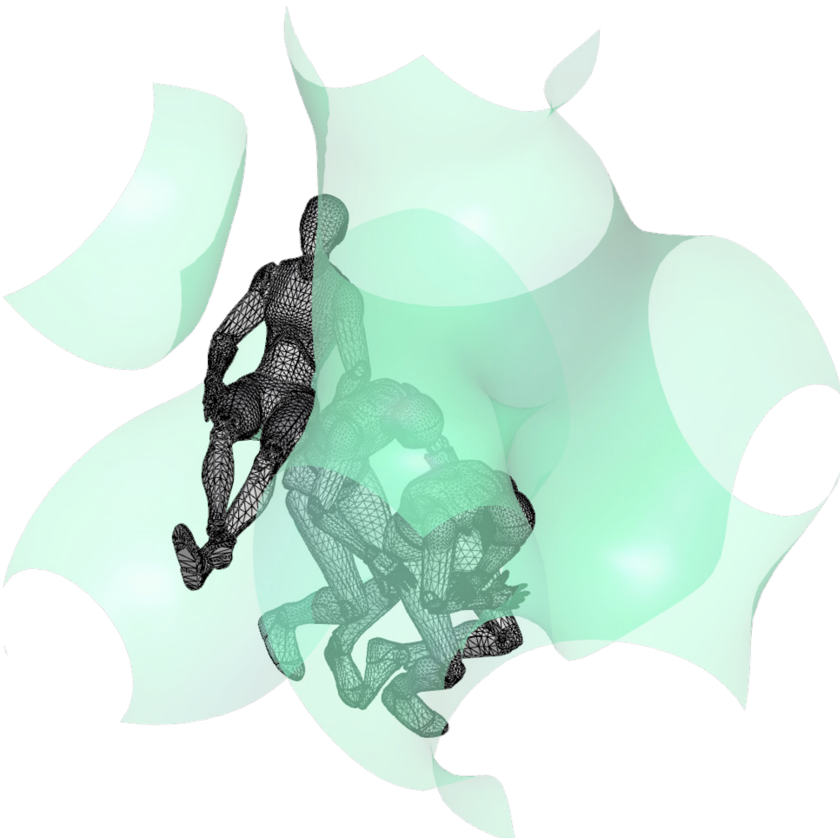
4. modify parameter



5. merge multiple attractors





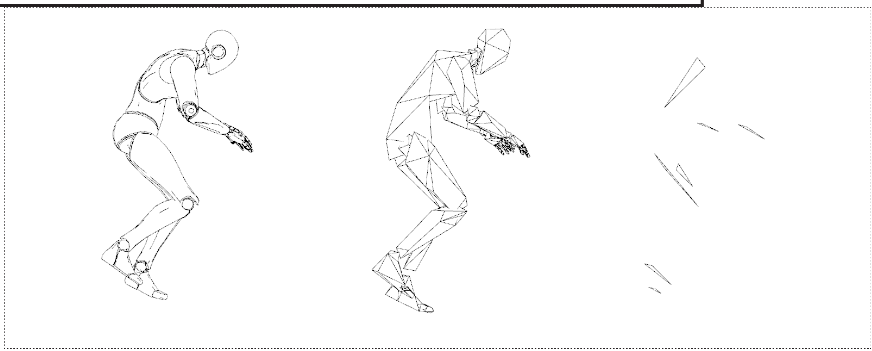


Dummy shown as time-lapse positions

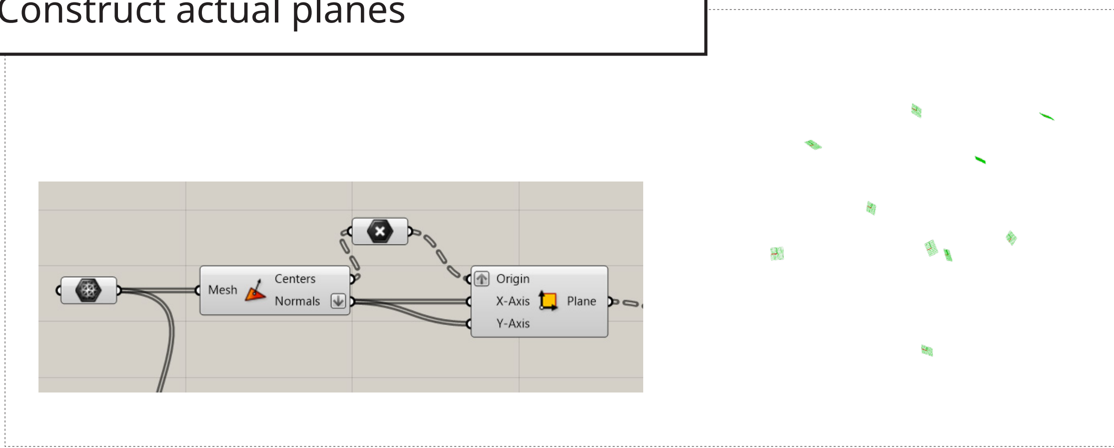
6.4 Evaluation of result

In order to test whether certain IsoValue would house sufficient volume and address user's reclaiming of the individual 'plumb line', the original visual and force anchors are revisited and abstracted.

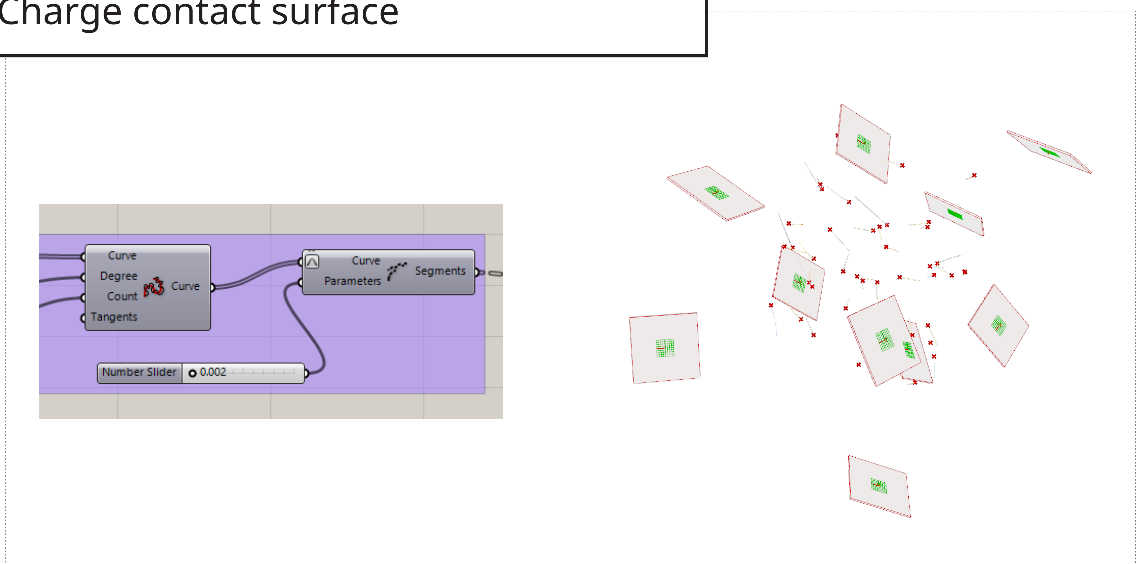
Manually find support and contact area



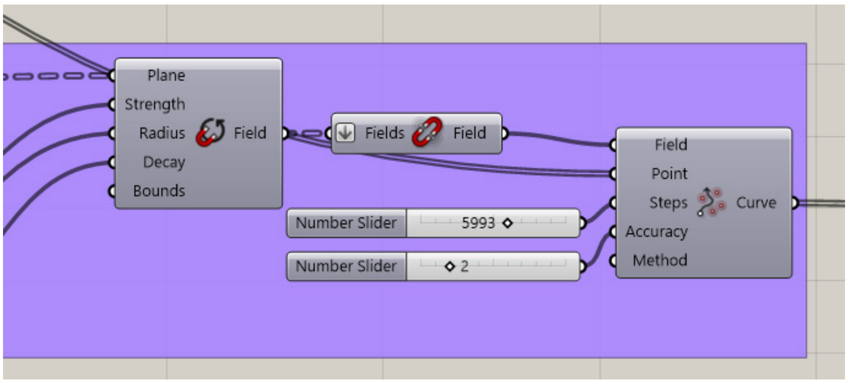
Construct actual planes

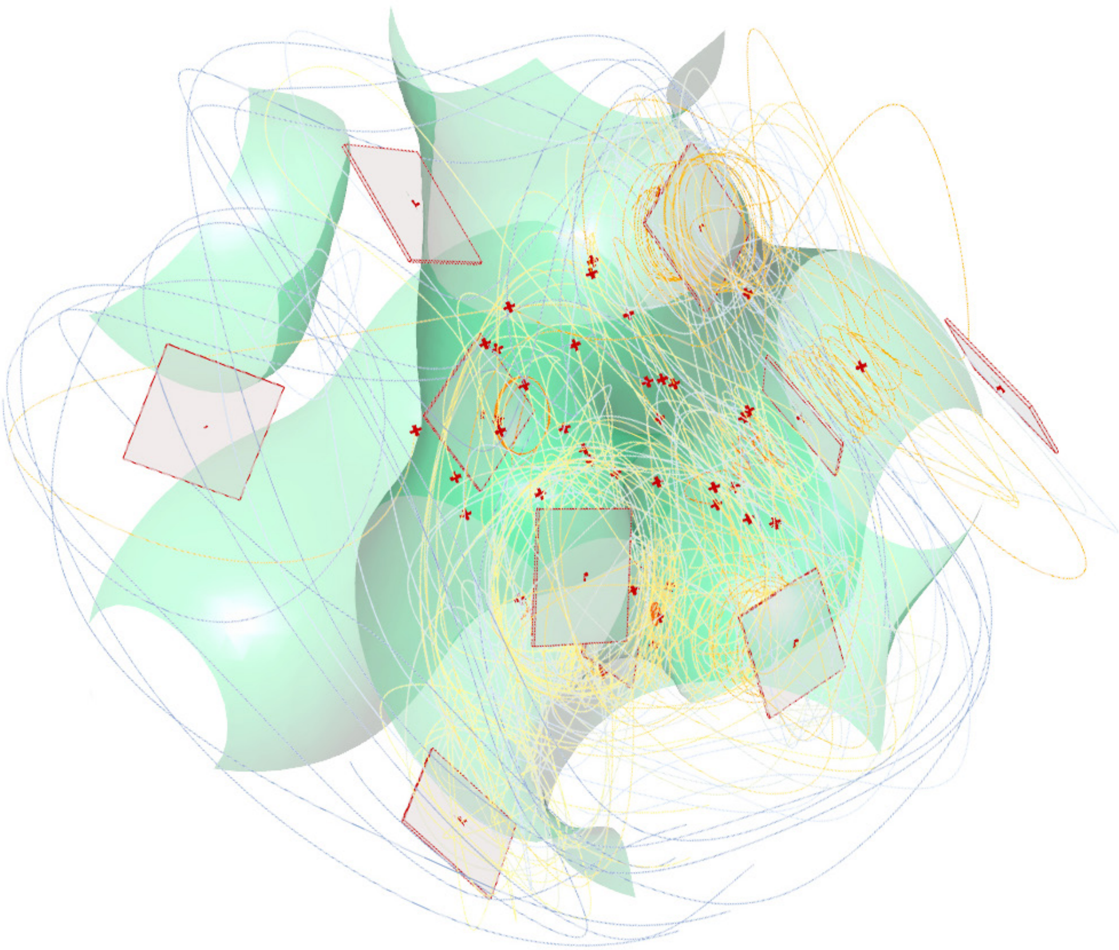


Charge contact surface



Visual leading lines simulation





7.0 RELEVANCE

7.1 Off-earth Relevance

Prevent illusion and maintain well-being for Lunar habitants

In Gibson's (2014) "The Ecological Approach to Visual Perception", he argued that poor spatial perception design can lead to severe cognitive load, or even illusion. 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 (NASA, 1971). The picture also shows the perception on the moon is less clear whether there's a hill or a pit in the distance.

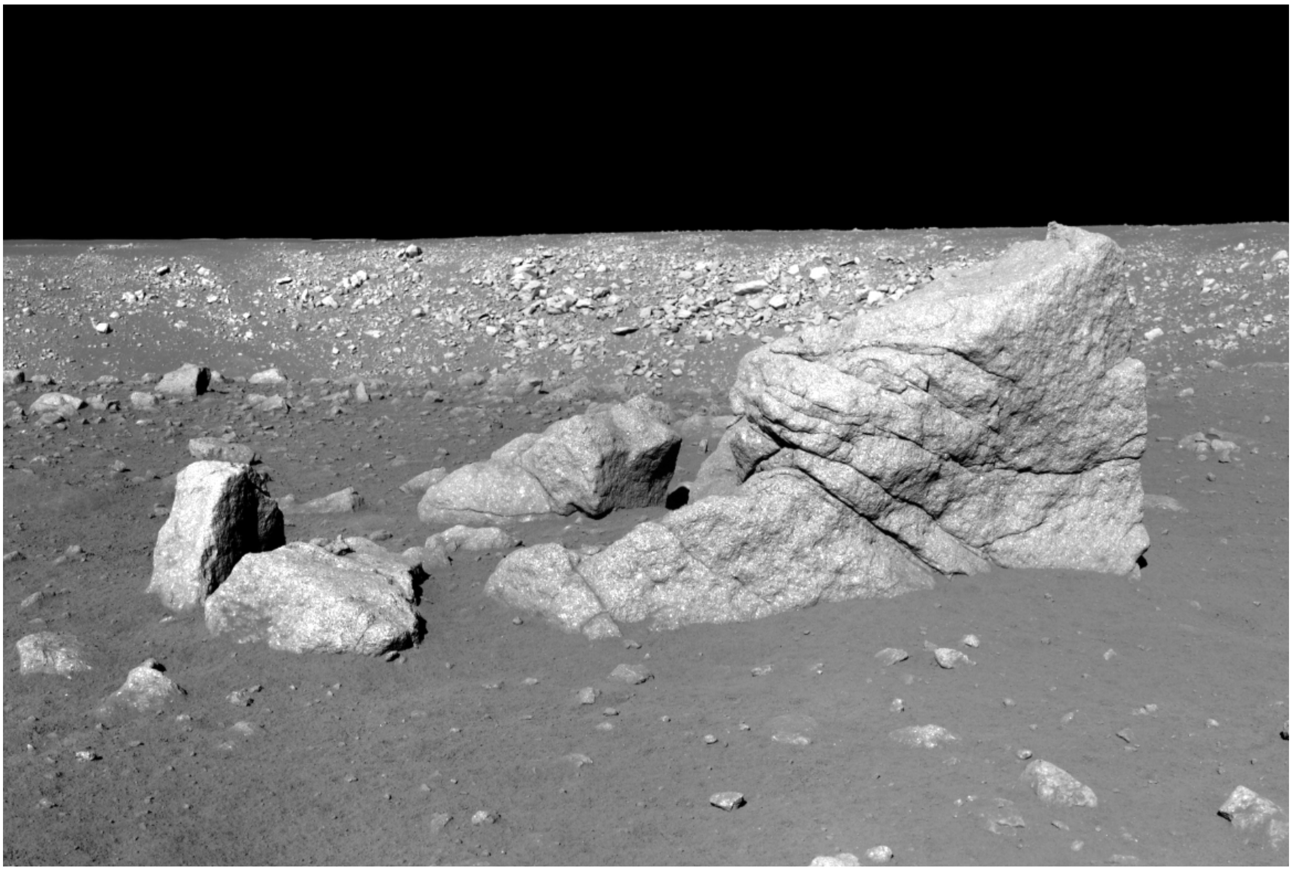


Fig 7.1: lunar surface (2020)

7.2 On-earth Relevance

Everyday of visual & object vertical

Coincidentally, in the last century, 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. Even without gravity, we can still obtain cues for spatial perception because geometry triggers our visual and muscular responses.

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.

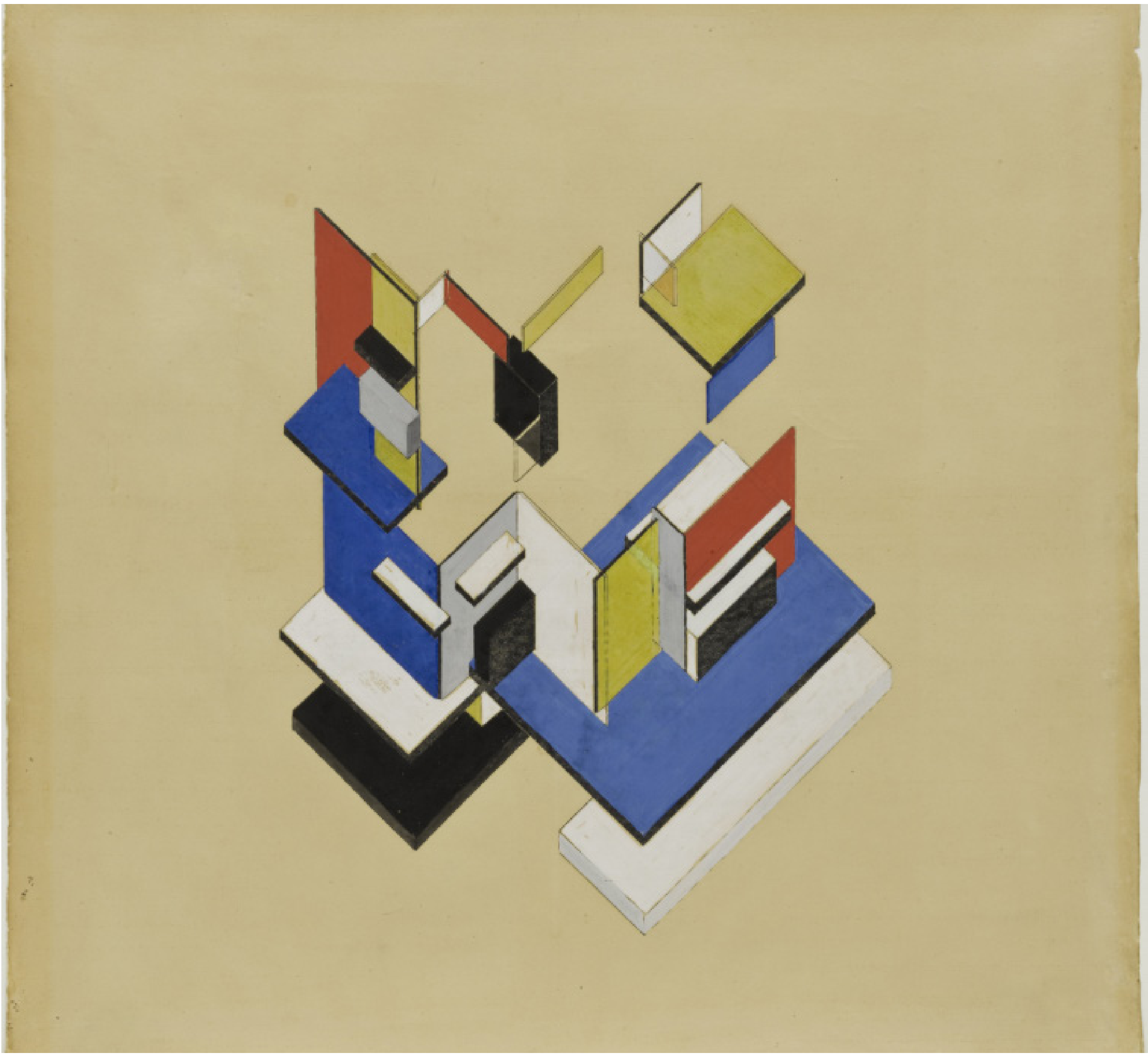


Fig 7.2: De Stijl movement (1923)

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Figures:

Fig 1.1: Mir. http://kvadratinterwoven.com/out-of-this-world-the-space-age-designs-of-galina-balashova

Fig 1.2: Reduced Gravity Walking Simulator - NASA 1963. https://www.netflix.com/nl/title/81466983

Fig 5.1: Lunar south pole.

Fig 5.2: Shackleton Crater. https://www.newscientist.com/article/2442113-should-we-put-a-frozen-backup-of-earths-life-on-the-moon/

Fig 5.3: Project timeline. Anthor's own

Fig 5.4: ESA practice moon walk underwater. https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Walking_on_the_Moon_underwater

Fig 5.5: Apollo 17 moon walk mission.

Fig 5.6: Oblique Function by Claude Parent and Paul Virilio. https://www.archdaily.com/1007880/claude-parent-architectural-fictions-exhibition

Fig 5.7: Diagram of the Extended Field of Vision by Herbert Bayer. https://www.are.na/block/7685309

Fig 7.1: lunar surface. https://www.scmp.com/news/china/policies-politics/article/1908638/china-releases-new-pictures-showing-stunning-details

Fig 7.2: Contra-Construction Project (Axonometric) (painting). https://www.moma.org/collection/terms/de-stijl

Fig 9.1-2: Output evaluation. Author's own

9.0 REFLECTION

After Millpede's iso-surface calculation, all anchors lose their original direction, making the result mesh unpredictable. This result is likely to be rooted in the original Gyroid calculation method, that \sin x\cos y+\sin y\cos z+\sin z\cos x=0, ignored all directional property of vector but automatically blend surfaces regardless of the UV sides.

While potential fix is possible to millpede's source code, this would not be the focus of this project. Instead, by emphasizing, or even reclaim the perception analysis again to the geometry outcome at each stage manually can be less efficient but more appropriate for my project.

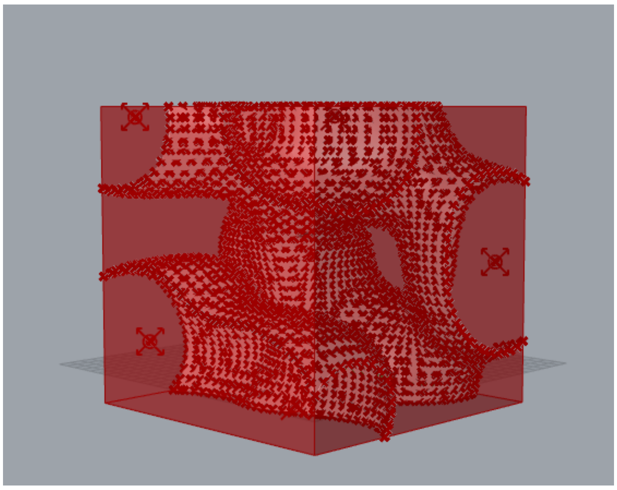

Fig 9.1: Point attractor list

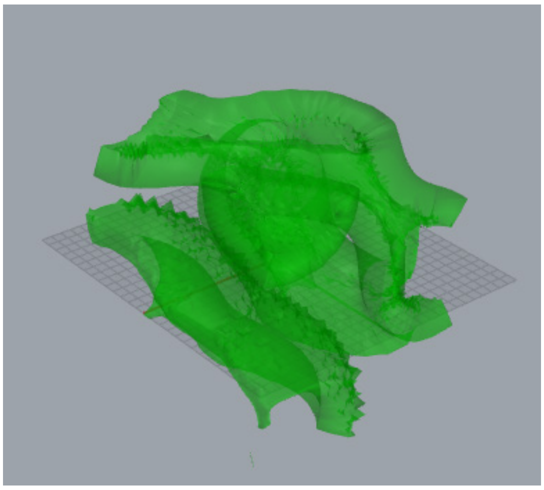

Fig 9.2: Point direction list