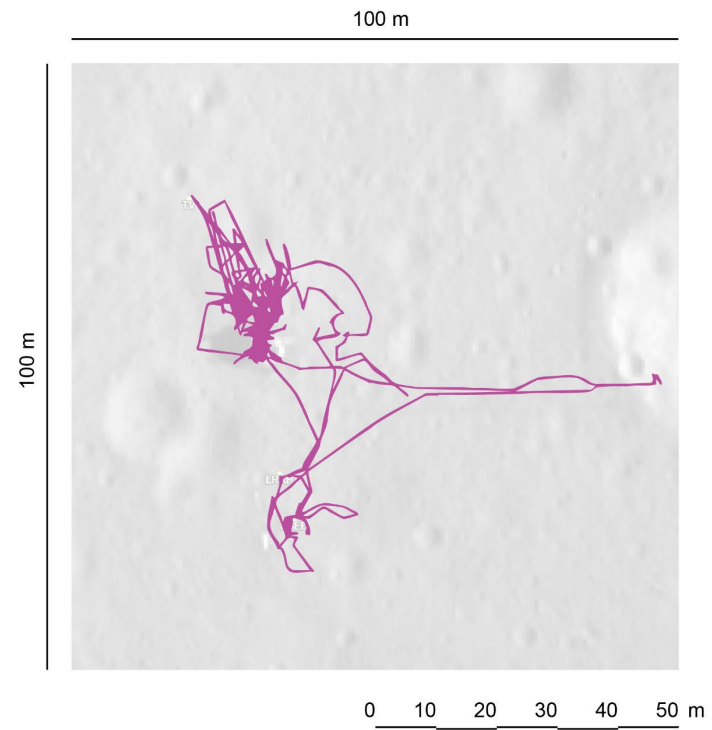


Adaptive Architecture on the Moon

Integrating mobile and inflatable approaches to address changing human needs on the Moon

1. Background:

Lunar colonization

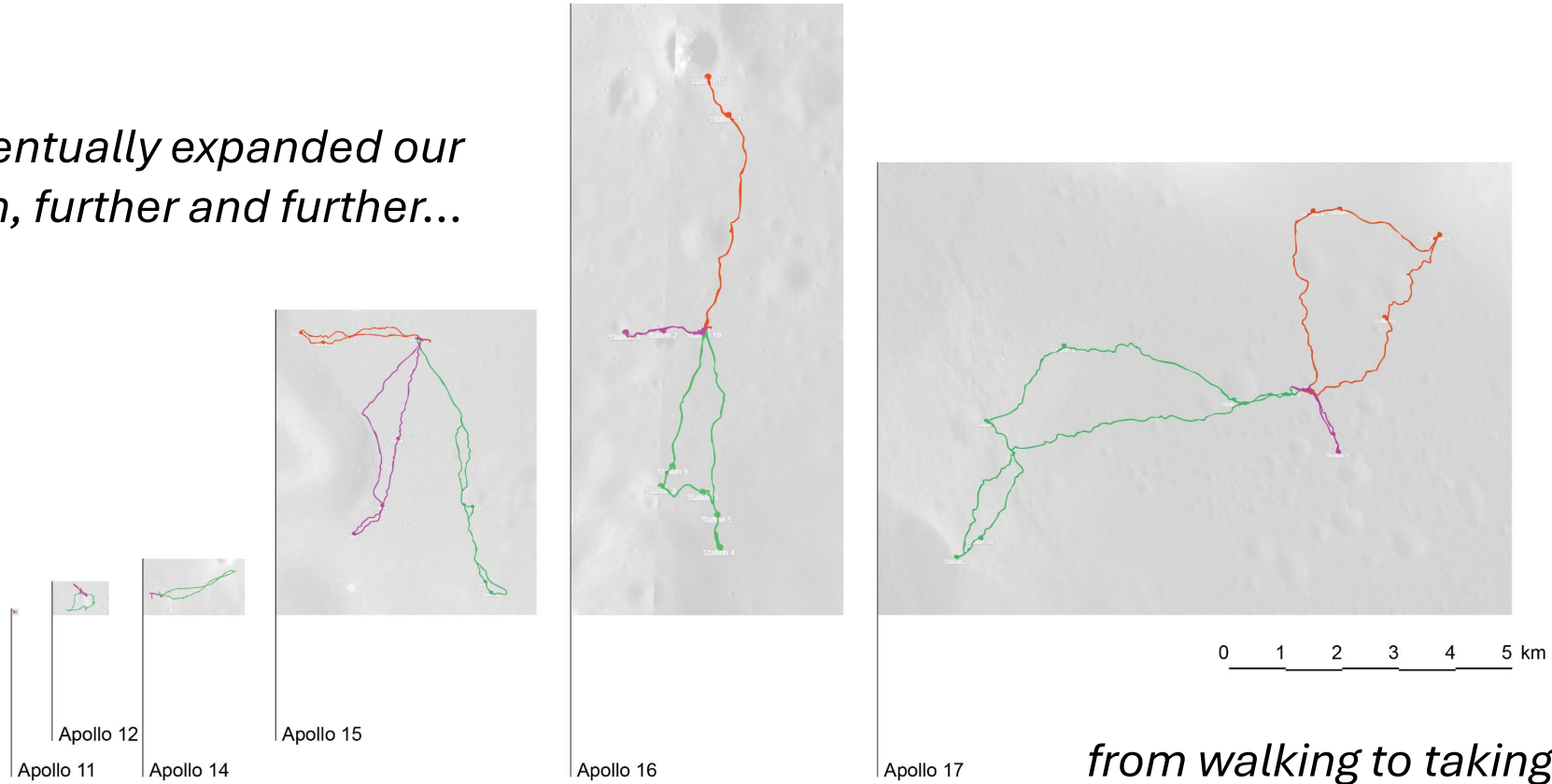


The very first landing on the Moon
*We **walked**...*

圖

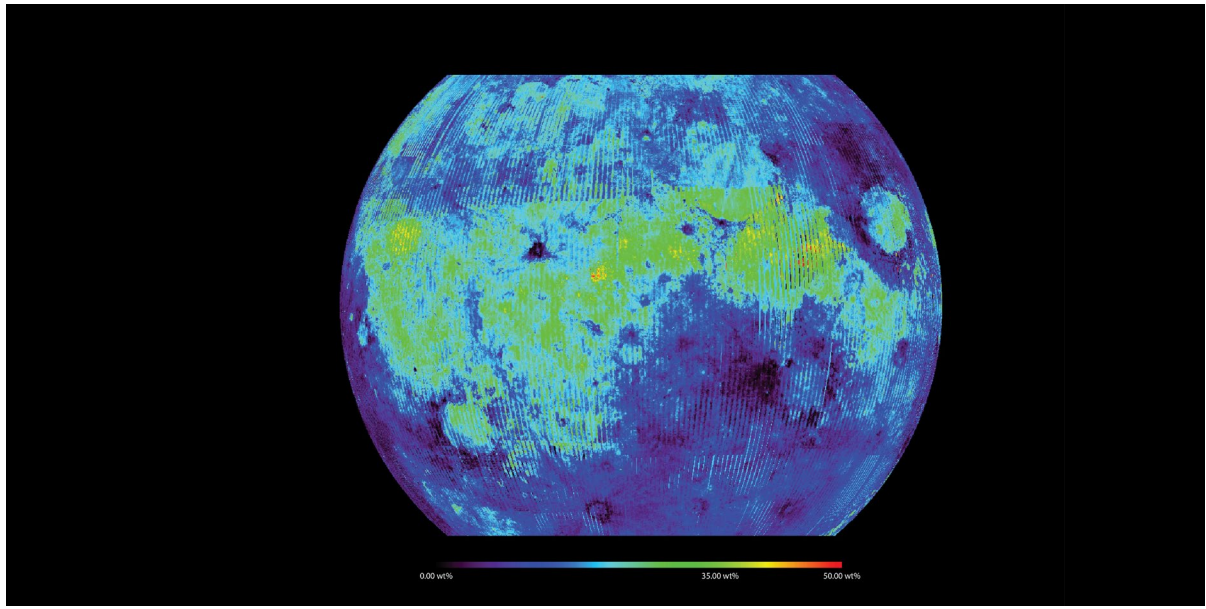
Apollo 11

And we eventually expanded our exploration, further and further...

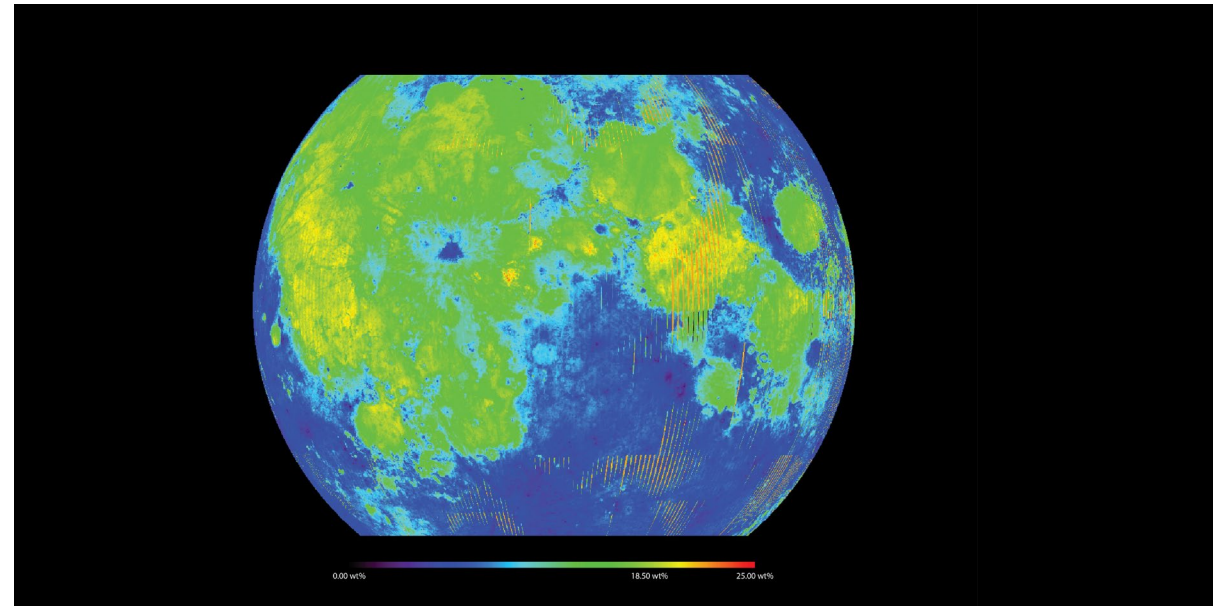


from walking to taking lunar rover...

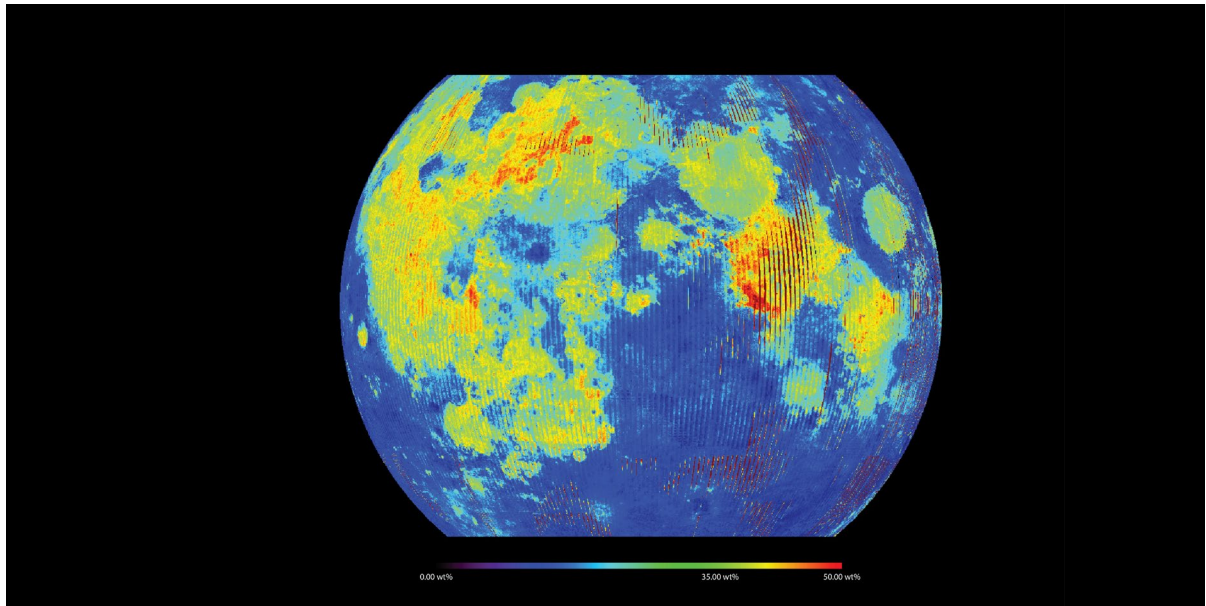
Increasing extents of exploration on the Moon



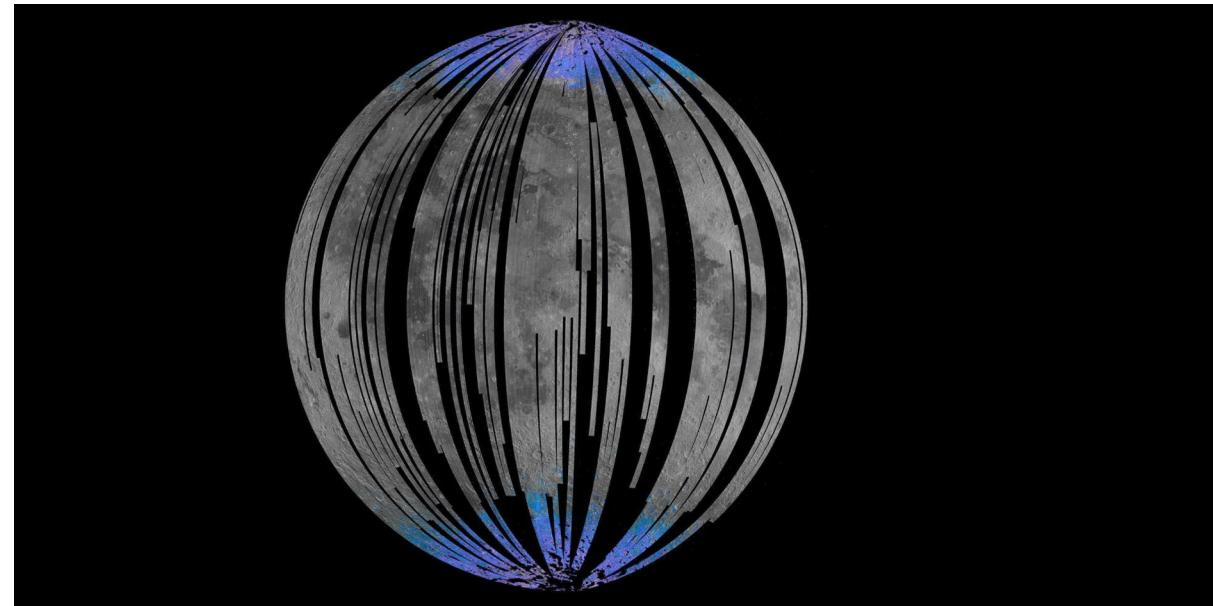
Orthopyroxene



Iron oxides



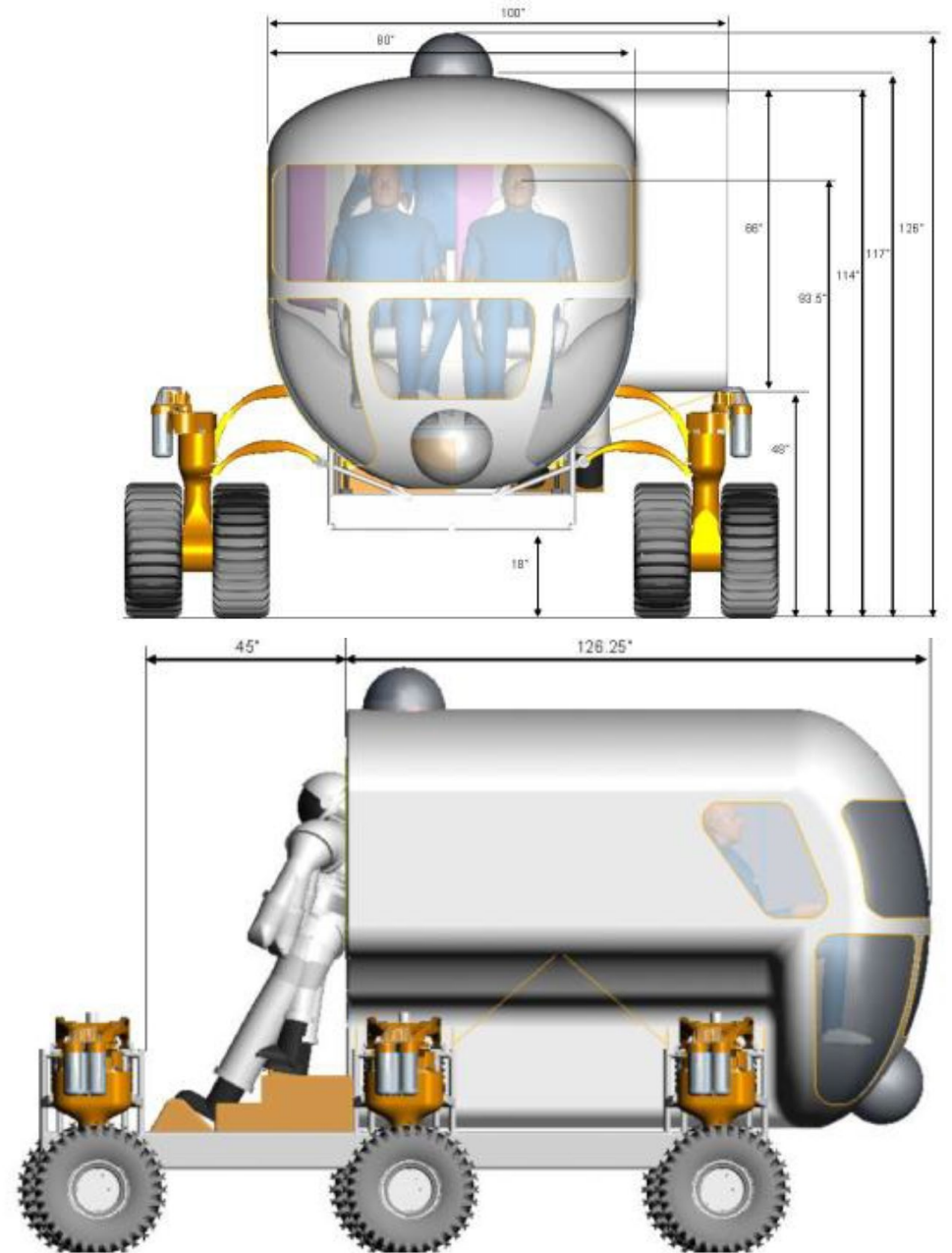
Clinopyroxene



Water

Scattered Resources on the Moon

1. Mobile lunar architecture



Existing development on lunar mobile architecture

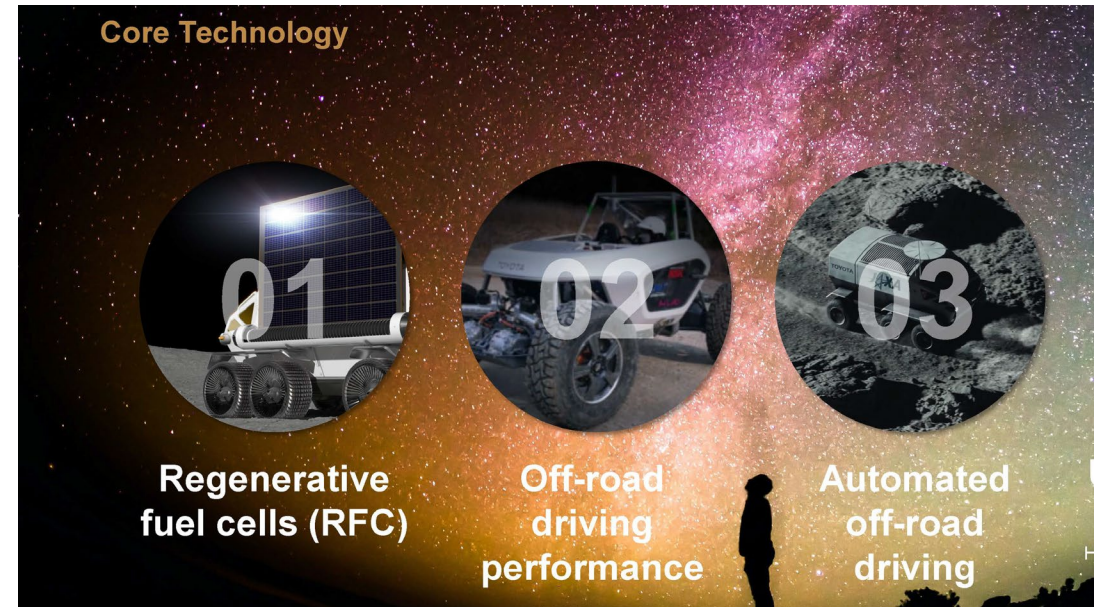


Exercising, eating, sleeping and toilet operation all in one space

“Doesn't seem ideal to block use of the toilet when a crewmember is exercising.”

A privacy curtain is all they have for toilet





Engineering-focused, not habitability focused



***How far** does a rocket travel...
to carry **only 10** NASA technology instruments?*

2. Inflatable lunar architecture



Inflatable architecture as a lightweight solution...



...focusing on material strength and inflation capacity

*Existing development focusing on **engineering aspects**
What more can we achieve through **architectural design**?*

Research Question

*How can mobile and inflatable approaches address
changing human needs on the Moon?*

2. Needs:

Changing *human needs on the moon*

Dynamic changes in the needs for social interaction



The need to retreat from and connect to others

Feedback from space analog mission HI-SEAS I

“...psychological importance of having a floor with a staircase to retreat to.”

“I felt 'connected' to the entire habitat at all times”

Communal or Private

It's not about one or the other, but the transition to freely switch between the two states

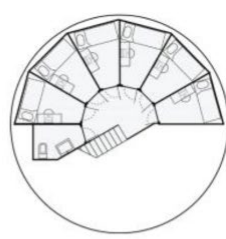
Needs for autonomy and reconfiguration

How astronauts' needs for autonomy,
competence and relatedness go hand in hand with
crewhealth and mission success - Results from
HI-SEAS IV

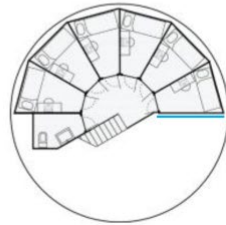
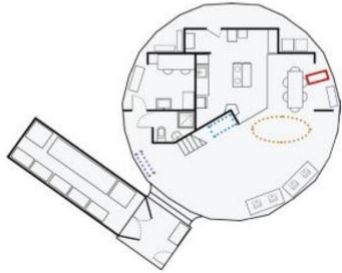
S. Goemaere et al.



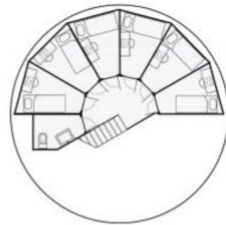
Designed by Angelo Vermeulen after participating in HI-SEAS I...
a co-created “starship” project: user self-building own habitat living in isolation



HISEAS I



HISEAS II



HISEAS III



HISEAS IV

Feedback from space analog mission HI-SEAS VI

“When we moved the treadmill in front of the window, you could look outside better and try to pretend you weren't stuck in the dome.”

“We rearranged a lot of the beds...”

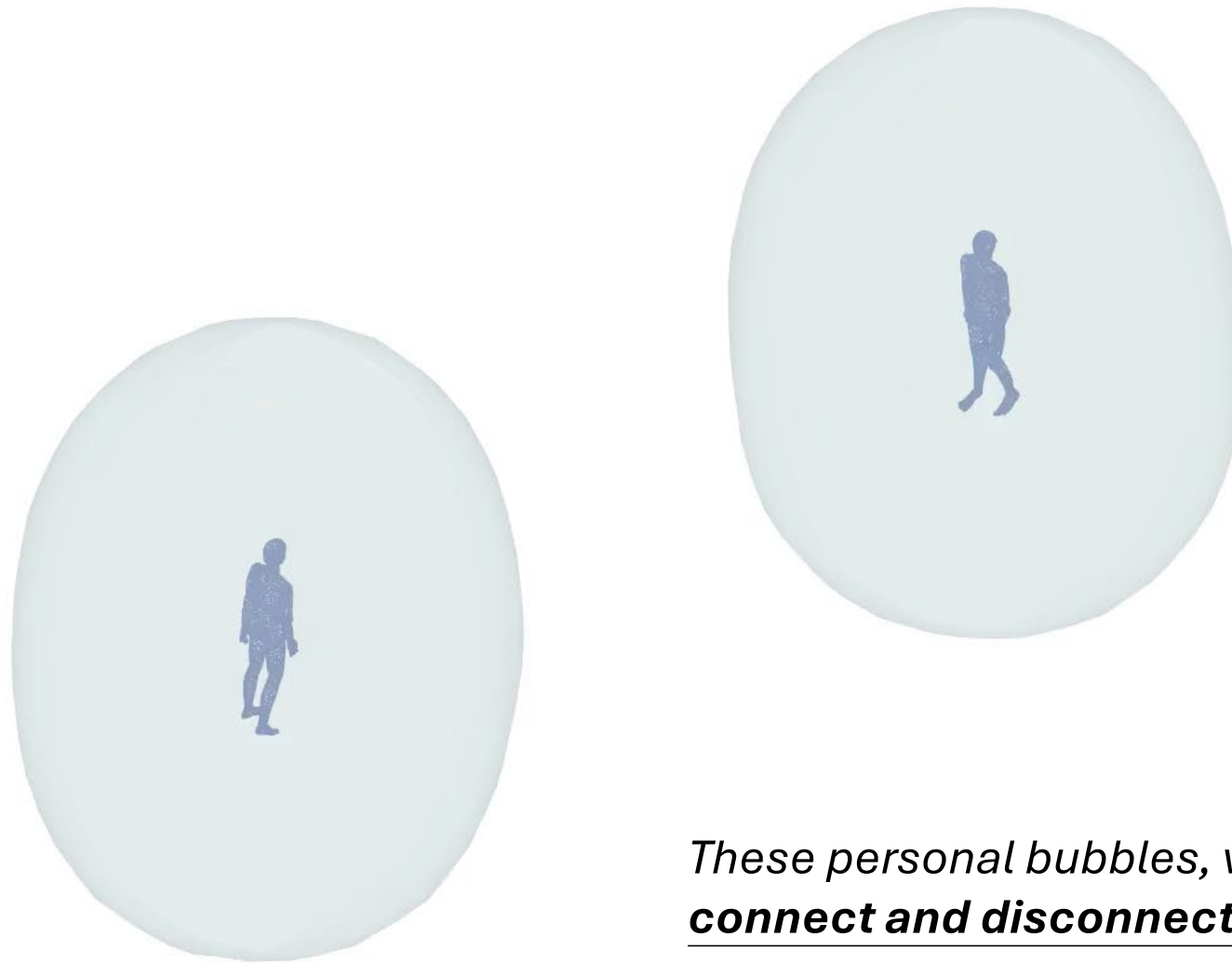
“Using both ends of the SeaCan for access would negate this programming conflict (between working and resting crew).”

HI-SEAS spatial reconfiguration record

Tristan Bassingthwaite. Habitat Design for the Long-Term Health of Inhabitants in ICE Environments



*We are indeed living in an invisible
personal bubble, by which our privacy is
controlled, our needs are fulfilled*



*These personal bubbles, vary from person to person,
connect and disconnect from time to time.*

Design solution to changing human needs?



3. Approach

(Dis)re-assembly: *Integrating mobile and inflatable architecture*

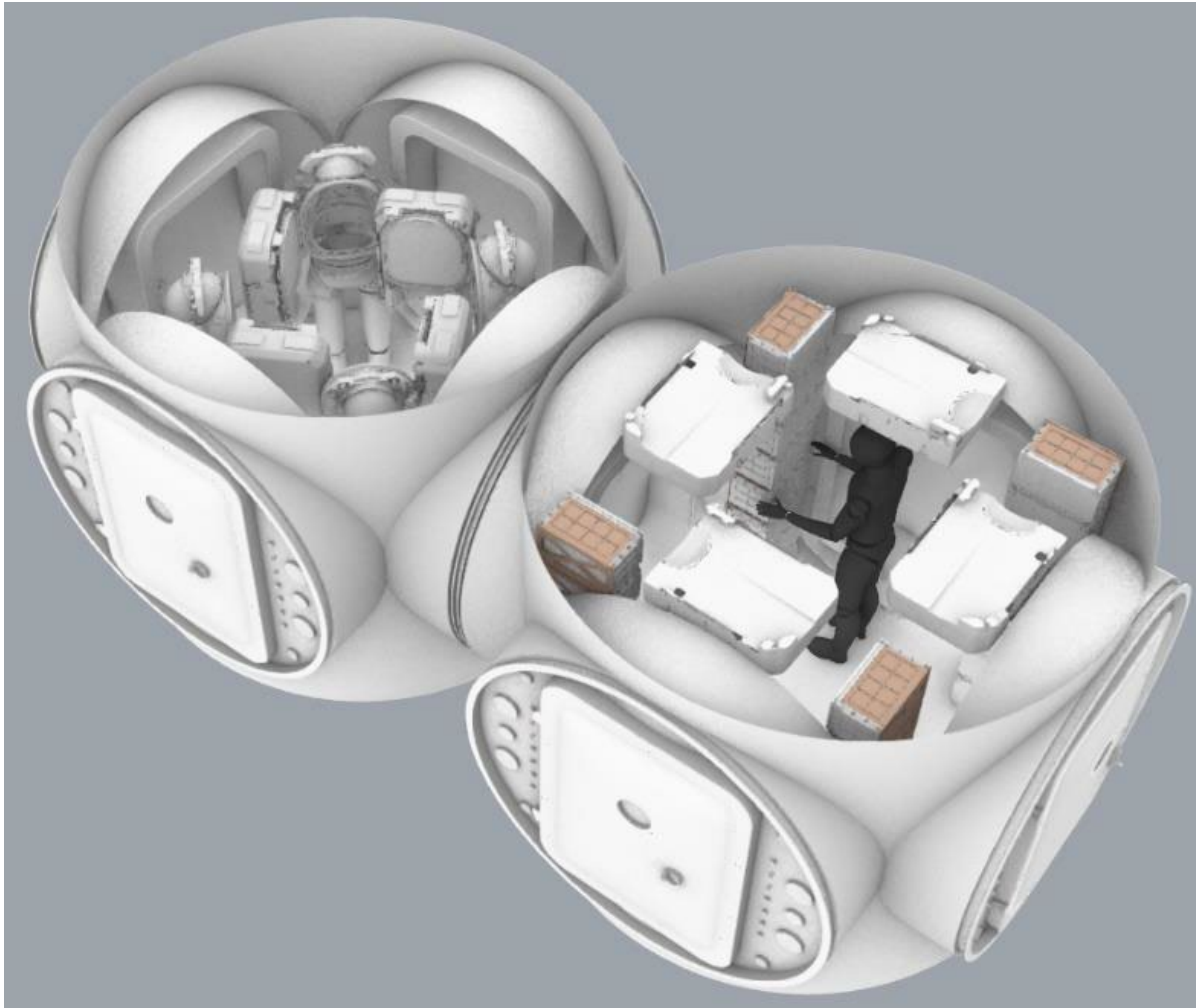


Rover-Rover

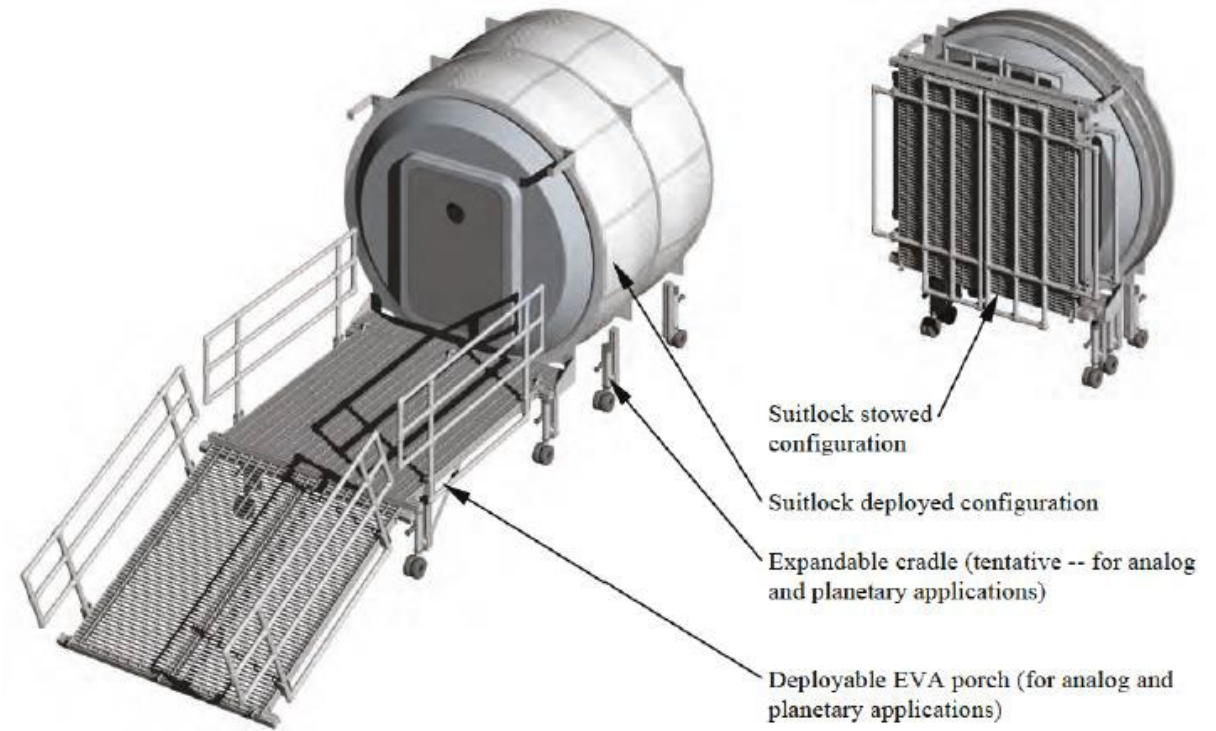


Rover-Habitat

Docking hatches in Small Pressurized Rover
Preliminary Report of the Small Pressurized Rover (SPR)



Multiple docking hatches forming nodes

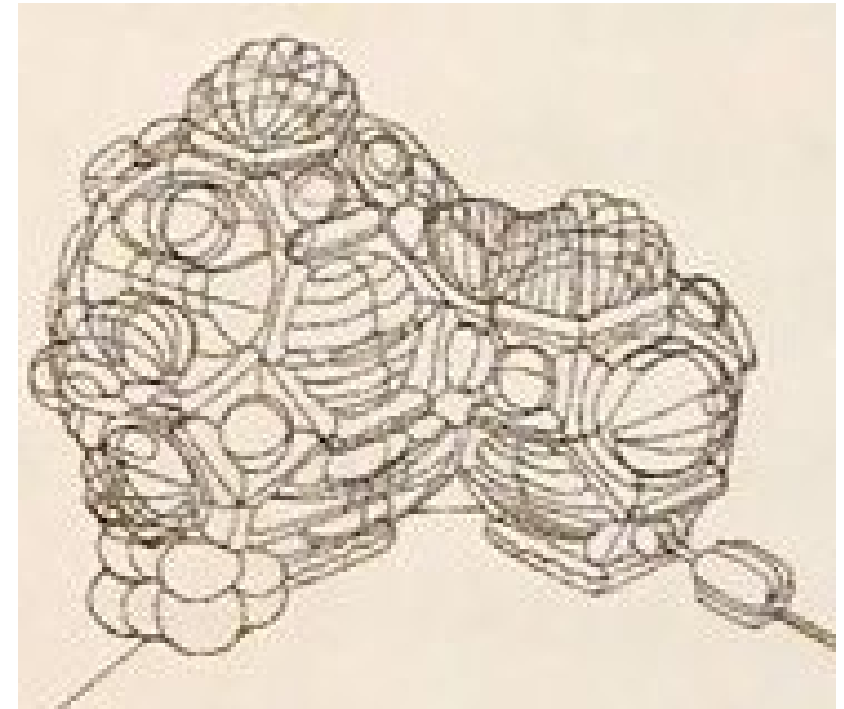
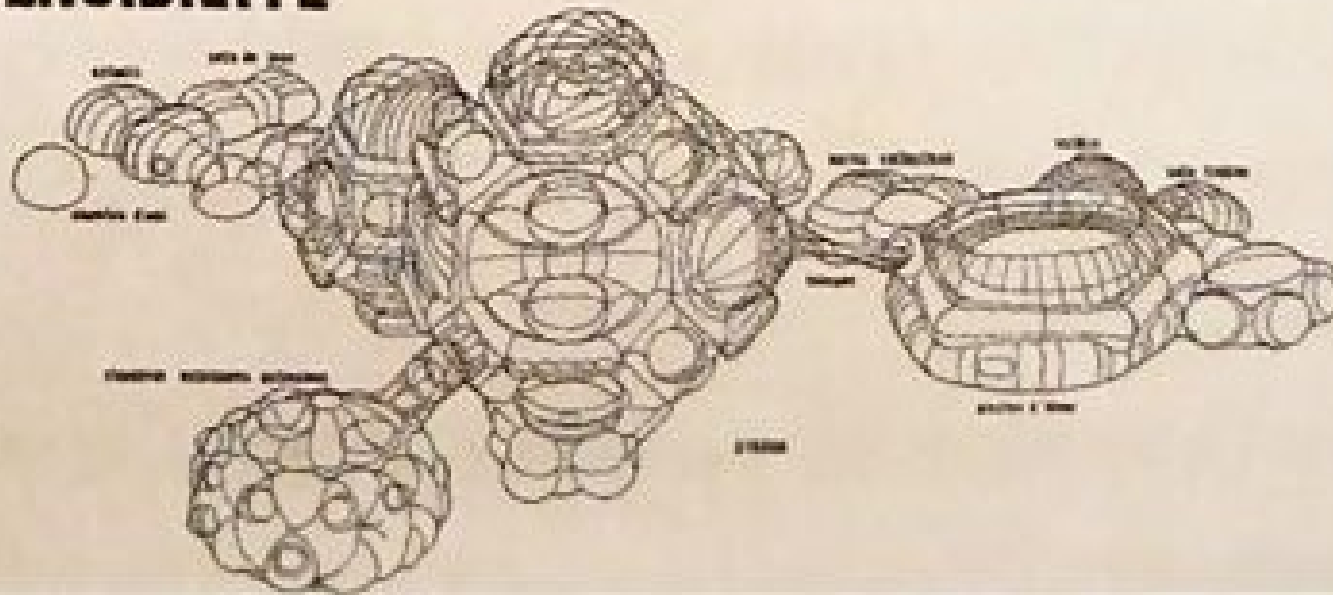


Docking hatches on inflatable structure

Potential configurations of docking hatches

Robert L. Howard, Jr.. A Multi-Functional, Two-Chamber Airlock Node for a Common Habitat Architecture

EXTENSIBILITE



Move + Join + Expand -> Growth

More complex connection of inflatable structures
Jean-Paul Jungmann. Dyodon-Habitation

4. Schematic Design: Proposed mission and scenarios

Architectural Segments

Artemis III Mission
~2027

Proposed design

**NASA plan to send
human to Mars
by 2040**

Human Lunar Return

Testing on crew and cargo transportation systems; deploy lunar communications relays; demonstrate technologies;

Foundational Exploration

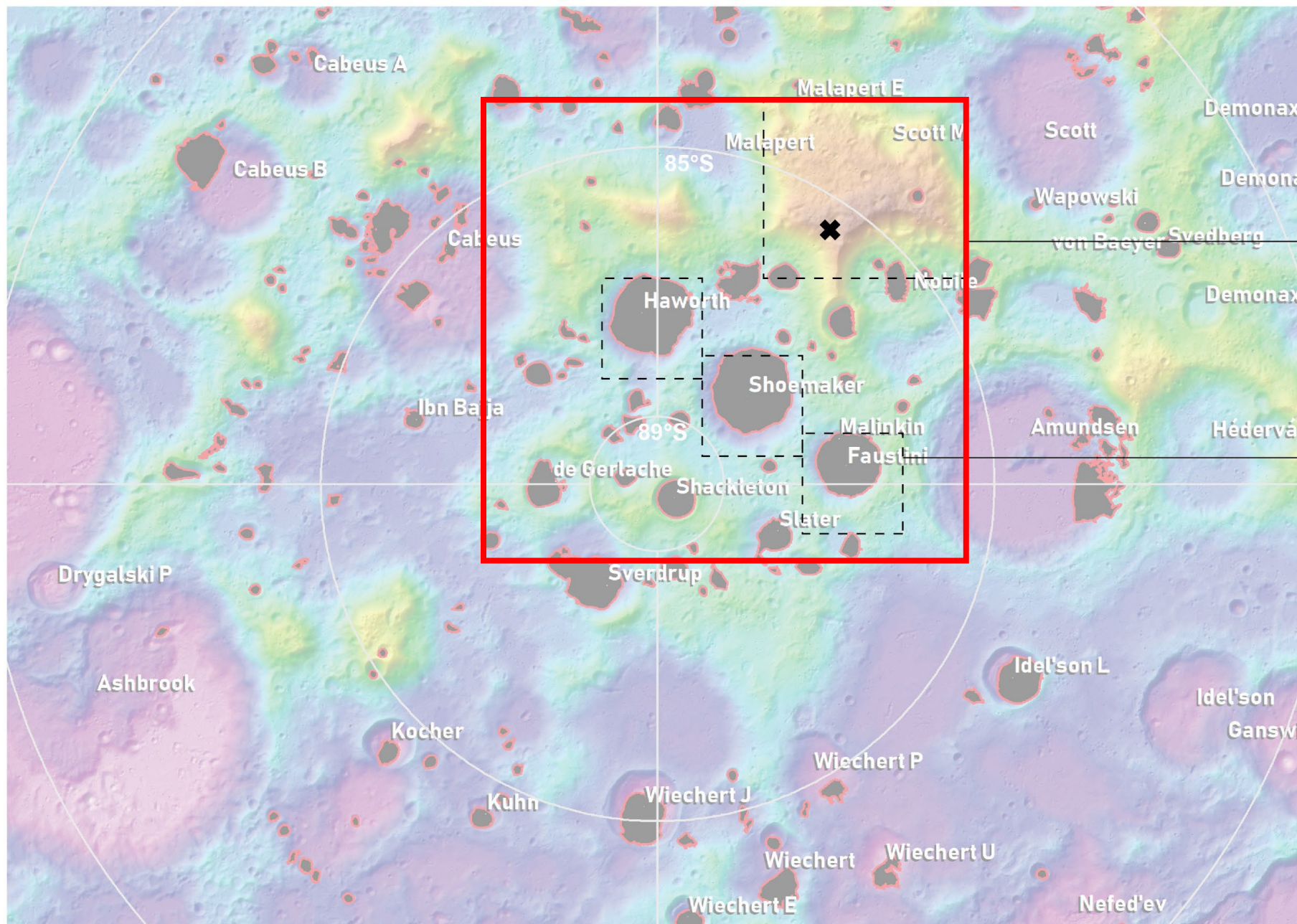
Surface missions with increased duration, expanded mobility, and regional exploration of the lunar South Pole.

Sustained Lunar Evolution

A long-term human presence on the Moon and sustainable development in lunar economy.

Humans to Mars

Testing on initial capabilities and systems necessary to safely travel to Mars.

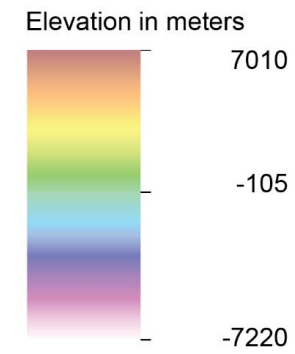


High elevation regions
with continuous exposure to sunlight

Permanently Shaded Regions (PSRs)

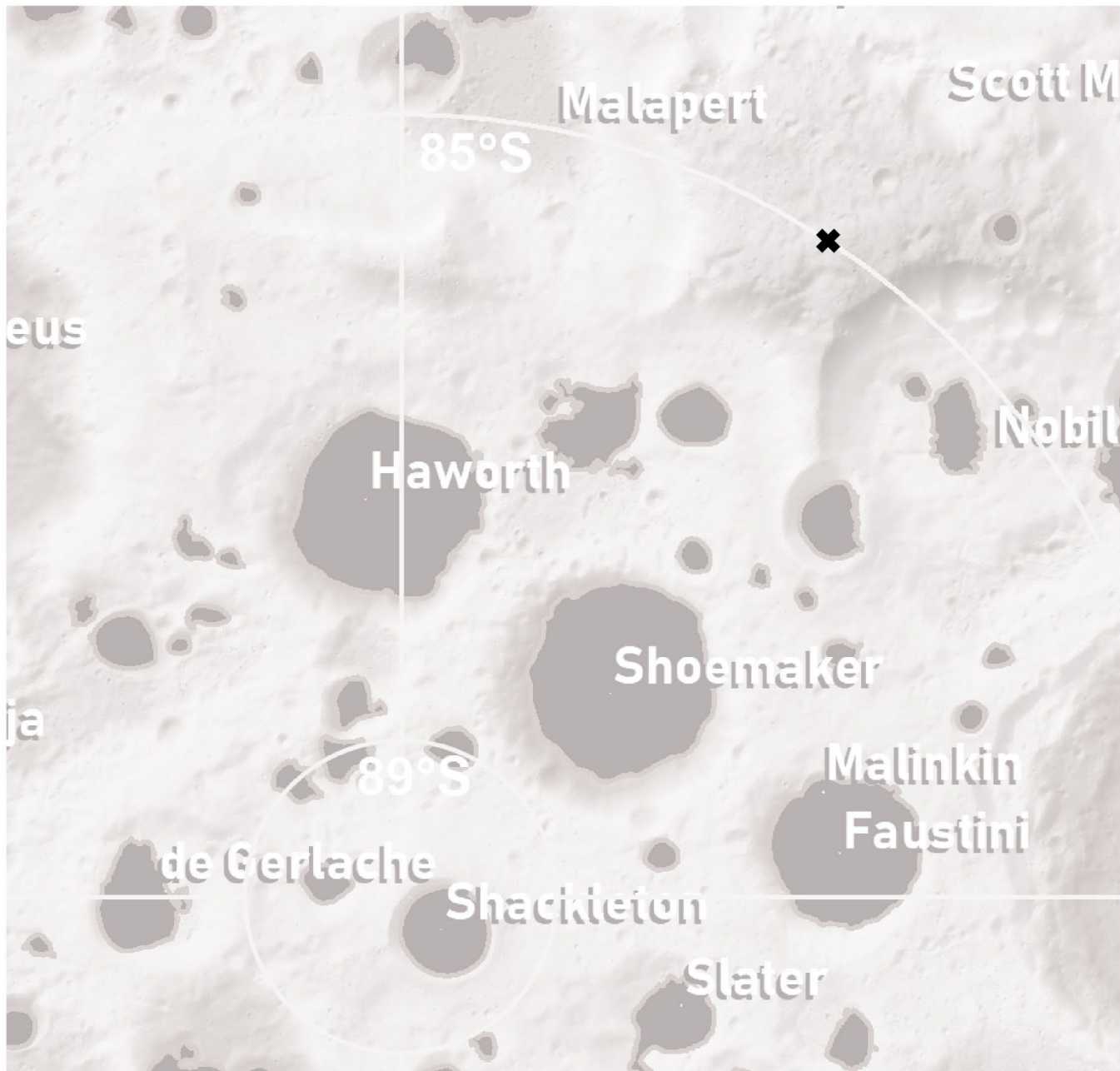
✕ Stationary habitat

■ Permanently Shaded Regions



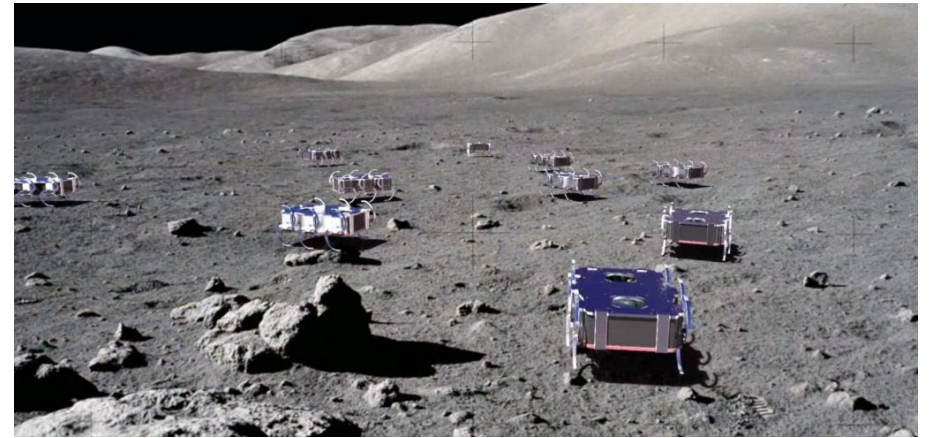
Lunar south pole

0 50 100 km

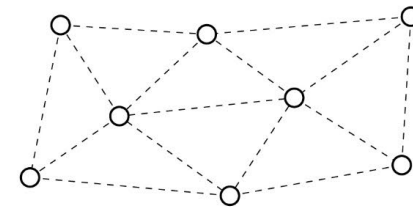


Lunar south pole

0 10 20 30 40 50 100 km



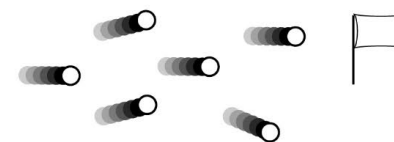
Swarm system on lunar automated driving



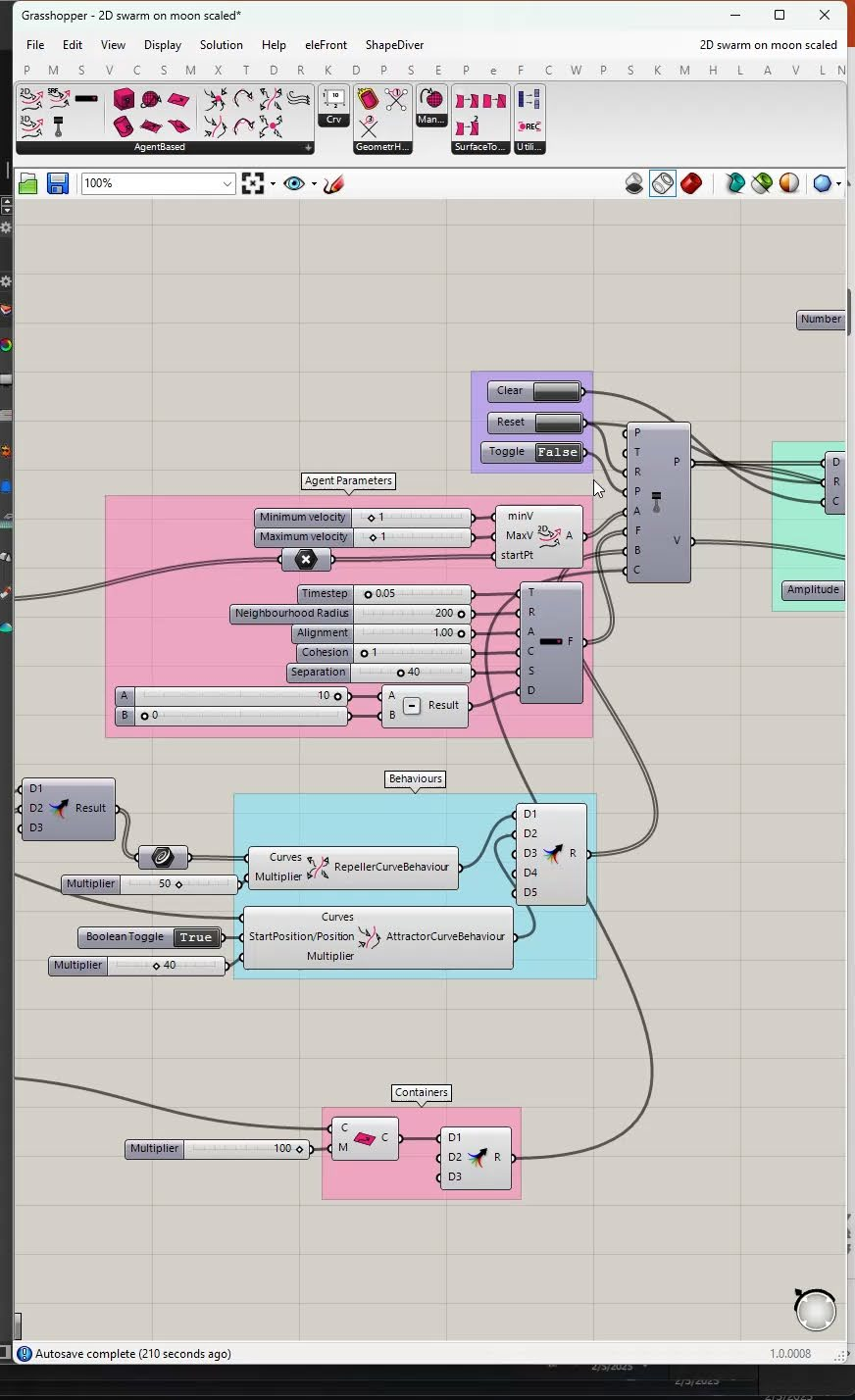
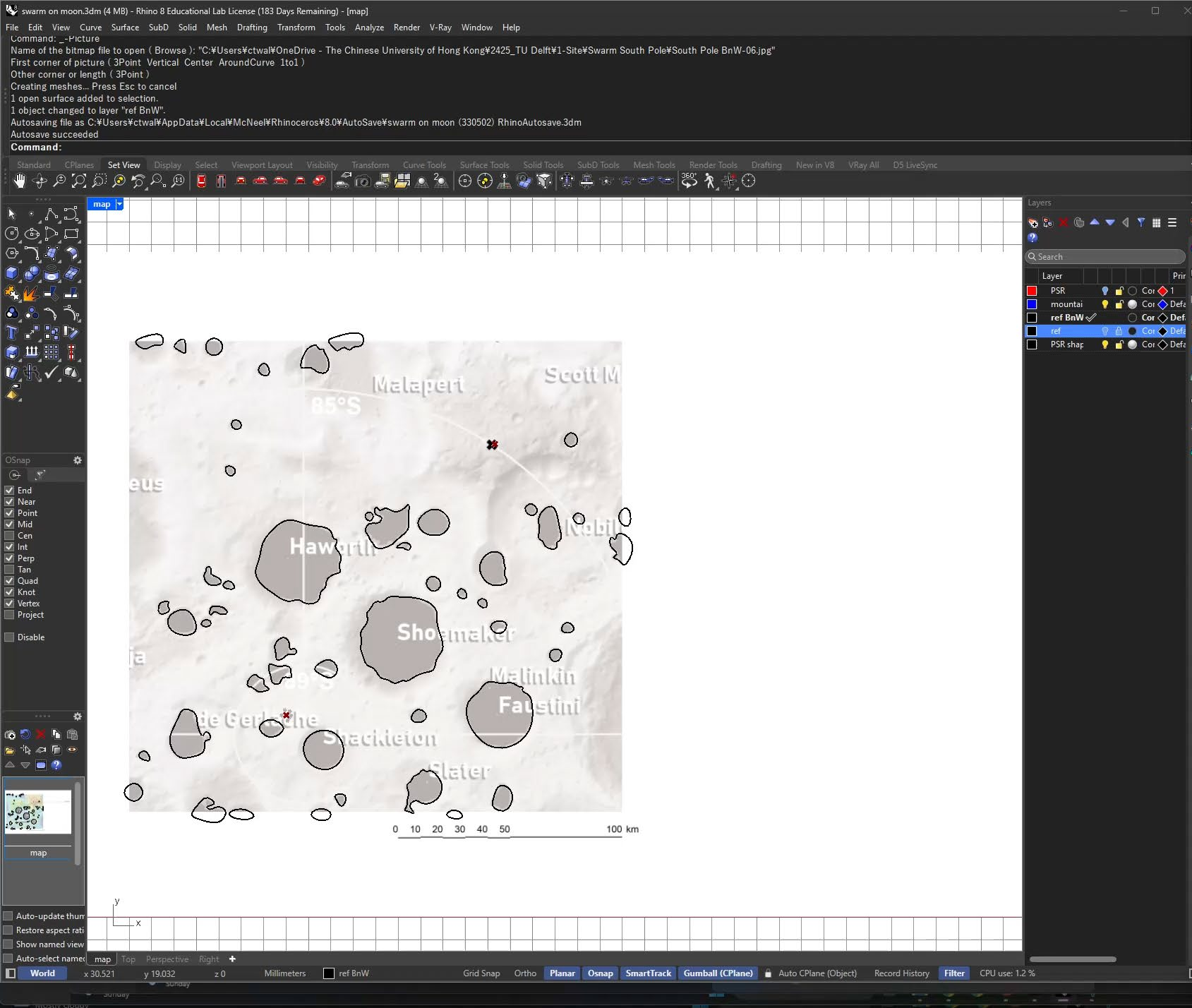
1. Maintaining a certain separation with each other

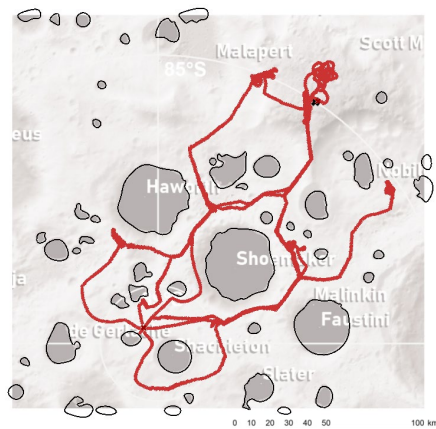


2. Avoiding obstacle

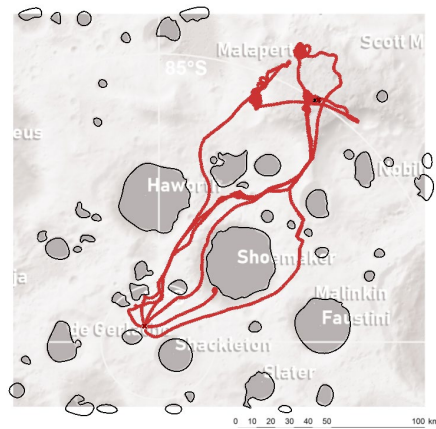


3. Moving as a group to a goal destination

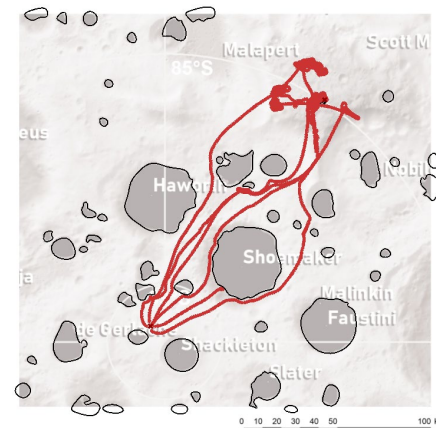




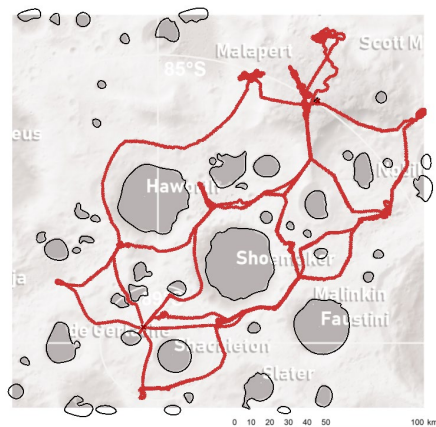
Swarm separation: 40
Obstacle repulsion: 50
Goal attractor: 10



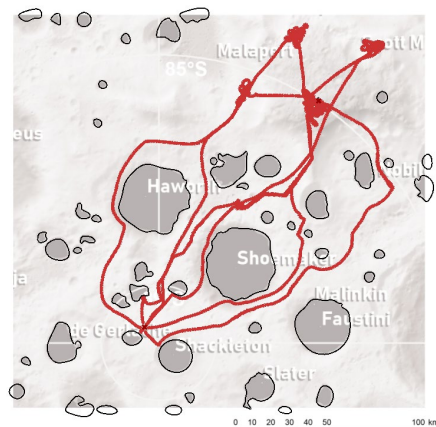
Swarm separation: 40
Obstacle repulsion: 50
Goal attractor: 40



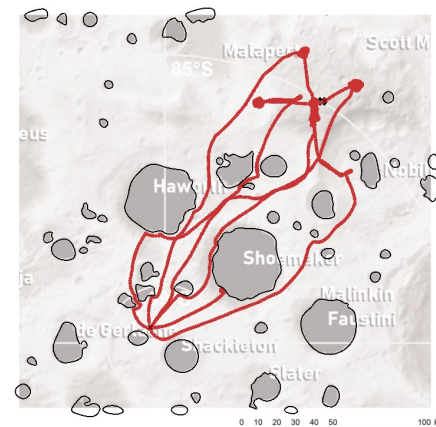
Swarm separation: 40
Obstacle repulsion: 50
Goal attractor: 70



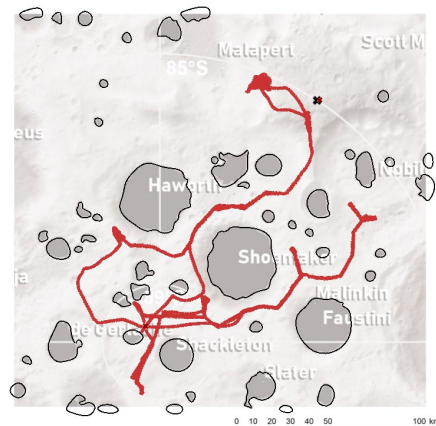
Swarm separation: 75
Obstacle repulsion: 50
Goal attractor: 10



Swarm separation: 75
Obstacle repulsion: 50
Goal attractor: 40



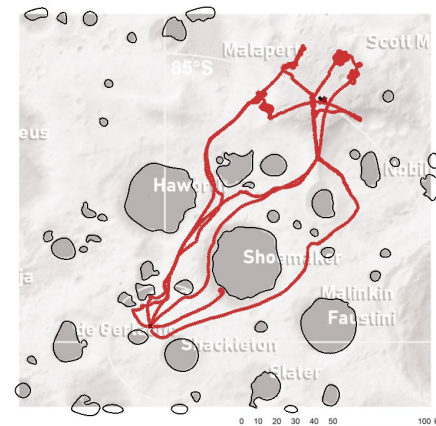
Swarm separation: 75
Obstacle repulsion: 50
Goal attractor: 70



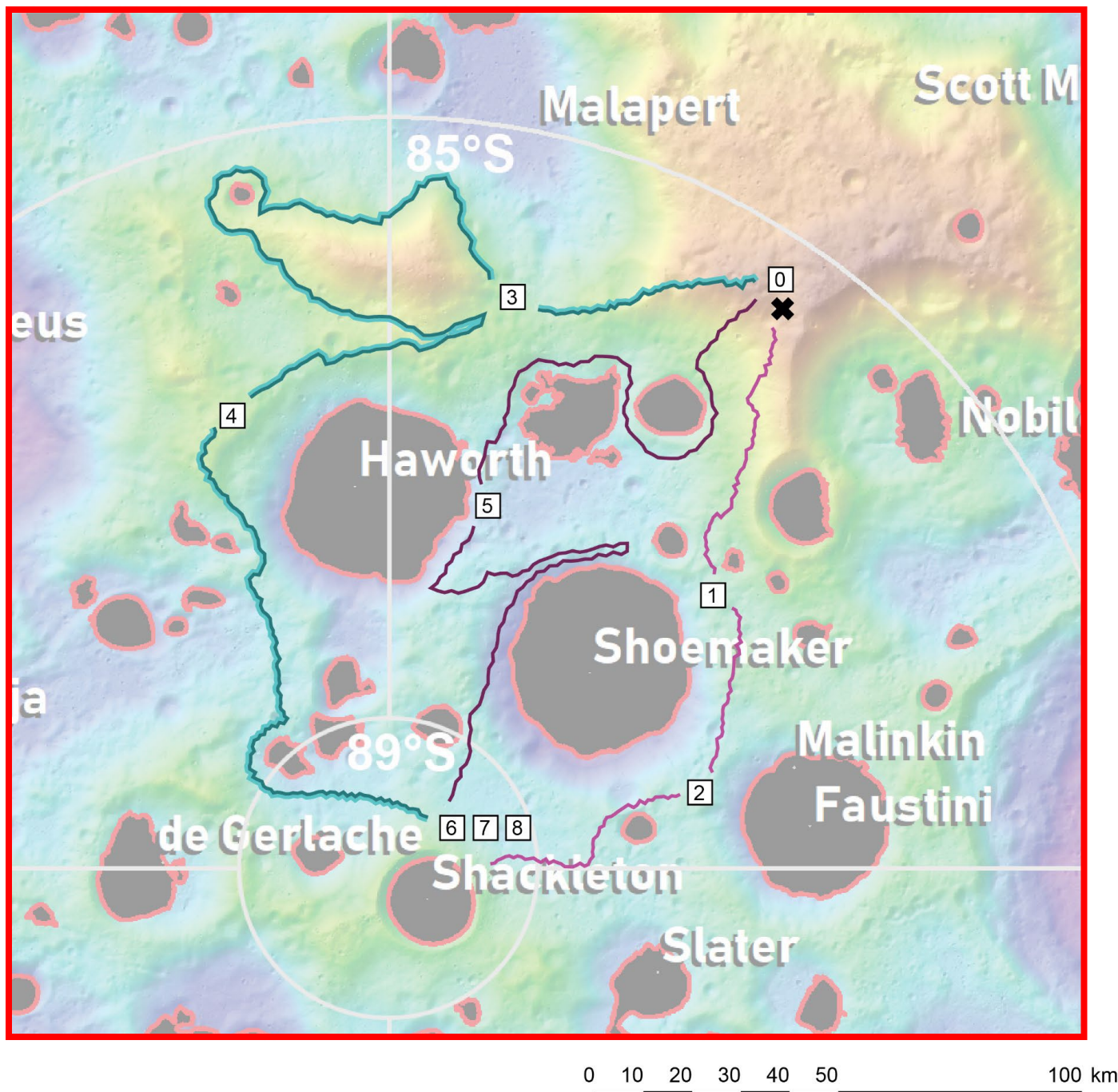
Swarm separation: 75
Obstacle repulsion: 80
Goal attractor: 10



Swarm separation: 75
Obstacle repulsion: 80
Goal attractor: 40



Swarm separation: 75
Obstacle repulsion: 80
Goal attractor: 70



✕ Stationary habitat

— Unit 1 route

— Unit 2 route

— Unit 3 route

0 Post-sleep tasks and departure from stationary habitat

1 Water ice resource extraction

2 ISRU processing plant inspection

3 Site investigation and sample collection

4 Collection of package from the Earth

5 Teleoperation of LTV for opportunistic observation

6 Teleoperation of LTV for site review on infrastructure deployment

7 Deployment of infrastructure (communications relay)

8 Parking of vehicles, pre-sleep tasks and return to stationary habitat

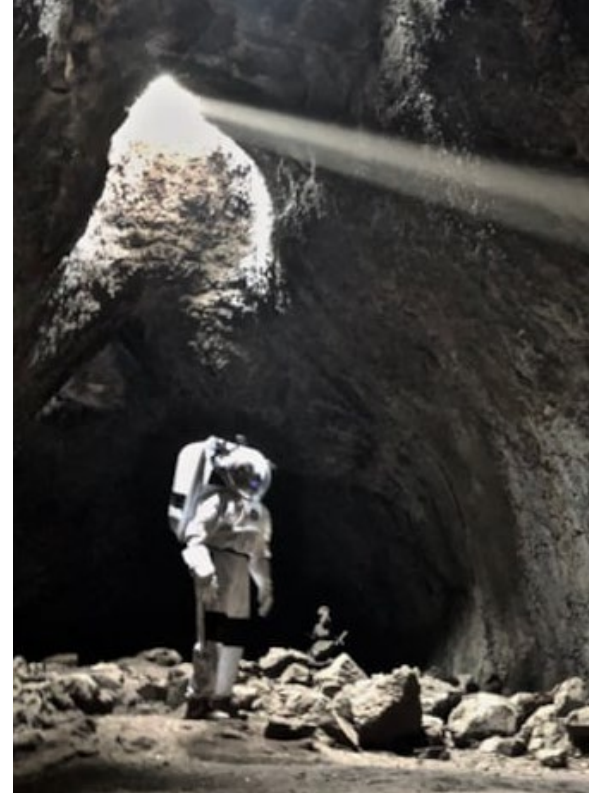




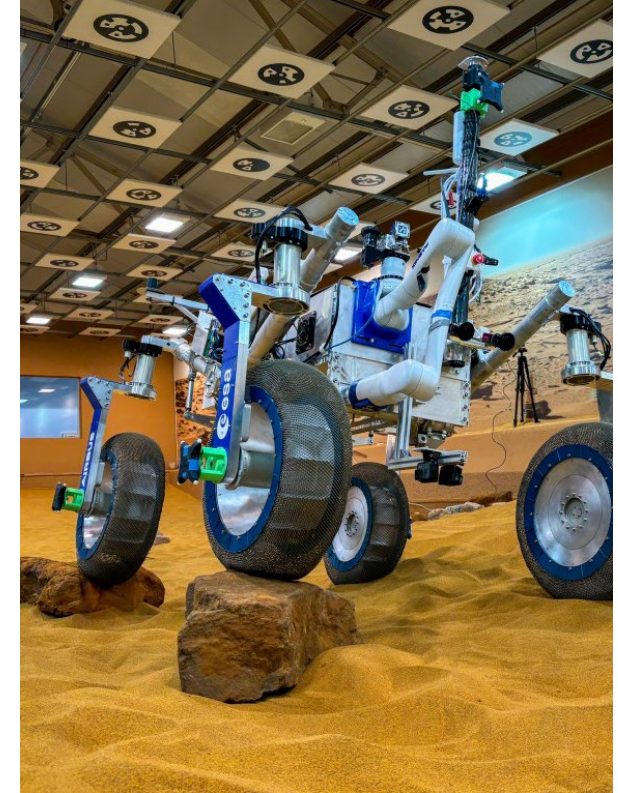
Engineering support



Commander/mission planning



In-person site investigation



Teleoperation of uncrewed lunar terrain vehicle (LTV) on risky sites

Designed astronaut roles and corresponding tasks

Engineering Support	07:00		private quarter
	07:30	waking up	private quarter
	08:00	body cleaning	washroom
	08:30	meal preparation	pantry
	09:00	breakfast	living room
	09:30	exercise	exercise
	10:00	meditation	meditation
	10:30	conference	meeting room
	11:00		meeting room
	11:30	drive to water ice resource site	cockpit
	12:00	water ice resource extraction	suitport
	12:30	lunch	living room
	13:00	drive to ISRU construction site	cockpit
	13:30	pre-EVA suit check	suitport
	14:00	ISRU construction inspection	EVA
	14:30	maintenance	maintenance
	15:00	clean-up interior	living room
	15:30	assembly	cockpit
	16:00	socialize	living room
	16:30	pickup tools for infrastructure deployment	workspace
	17:00	task briefing	workspace
	17:30	pre-EVA suit check	suitport
	18:00	deployment of infrastructure	EVA
	18:30	mission debrief	workspace
	19:00	meal preparation	pantry
	19:30	dinner	living room
	20:00	group movie night	leisure
	20:30	games	leisure
	21:00		leisure
	21:30	body cleaning	washroom
	22:00	sleep	private quarter

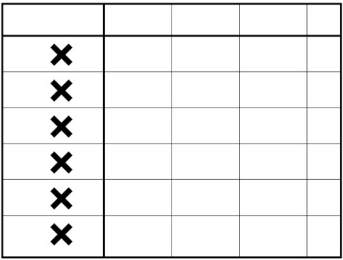
Commander + Surveyor	07:00	waking up	private quarter	waking up	private quarter
	07:30	body cleaning	washroom	body cleaning	private quarter
	08:00	exercise	exercise	meal preparation	washroom
	08:30		exercise		pantry
	09:00	breakfast	living room	breakfast	living room
	09:30	mission review	workspace	exercise	exercise
	10:00	mission planning	workspace	meditation	meditation
	10:30	conference	meeting room	conference	meeting room
	11:00		meeting room		meeting room
	11:30	mission planning	cockpit	drive to science site and observe potential site	cockpit
	12:00	pre-EVA suit check	suitport	pre-EVA suit check	suitport
	12:30	site investigation and sample collection	EVA	site investigation and sample collection	EVA
	13:00	report writing	workspace	drive to package collection area and observe potential site	cockpit
	13:30	report writing	living room	collection of package from the Earth	EVA
	14:00	unloading package	storage	unloading package	storage
	14:30	lunch	living room	lunch	living room
	15:00	drive to group assembly point	cockpit	clean-up interior	living room
	15:30	assembly	cockpit	assembly	cockpit
	16:00	socialize	living room	socialize	living room
	16:30	pickup tools for infrastructure deployment	workspace	pickup tools for infrastructure deployment	workspace
	17:00	task briefing	workspace	task briefing	workspace
	17:30	pre-EVA suit check	suitport	pre-EVA suit check	suitport
	18:00	deployment of infrastructure	EVA	deployment of infrastructure	EVA
	18:30	mission debrief	meeting room	mission debrief	workspace
	19:00	mission planning	workspace	meal preparation	pantry
	19:30	dinner	living room	dinner	living room
	20:00	group movie night	leisure	group movie night	leisure
	20:30	games	leisure	games	leisure
	21:00		leisure		leisure
	21:30	body cleaning	washroom	body cleaning	washroom
	22:00	sleep	private quarter	sleep	private quarter

LTV Specialist	07:00	waking up	private quarter
	07:30	body cleaning	washroom
	08:00	exercise	exercise
	08:30	leisure	meditation
	09:00	meal preparation	pantry
	09:30	breakfast	living room
	10:00	review potential site list	workspace
	10:30	conference	meeting room
	11:00		meeting room
	11:30	drive to PSR	cockpit
	12:00	teleoperation of LTV	cockpit
	12:30	report writing	workspace
	13:00	lunch	living room
	13:30		living room
	14:00	drive to potential site for deployment of infrastructure	cockpit
	14:30	teleoperation of LTV	cockpit
	15:00	clean-up interior	living room
	15:30	assembly	cockpit
	16:00	last-minute site review	workspace
	16:30	last-minute site review	workspace
	17:00	task briefing	workspace
	17:30	teleoperation of LTV	cockpit
	18:00	teleoperation of LTV	cockpit
	18:30	mission debrief	workspace
	19:00	mission planning	workspace
	19:30	dinner	living room
	20:00	group movie night	leisure
	20:30	call with family	private quarter
	21:00	body cleaning	washroom
	21:30	sleep	private quarter
	22:00		private quarter

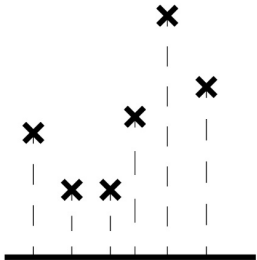
Schedule designed for each role

		volume			social interaction				relative position		compressable/relatively fixed	
category	room	minimum compressed volume (m3)	minimum functioning volume (m3)	total volume for 4 inhabitants (m3)	per person	shared facility	privacy	noise	view	relative height	open space	equipment
private	private quarter	2	5	20			5	1		4		
private	suitport	2	2	8			5	1		1		
private	washroom	2	3	12			5	1		1		
living	living room	5	8	32			1	5		3		
living	pantry	5	8	12			2	4		1		
leisure	exercise	0	5	20			2	3		5		
leisure	leisure	0	5	20			1	5		5		
leisure	meditation	0	4	16			4	1		5		
service	ECLSS	7	7	28			1	2		1		
service	food storage	3	3	12			1	3		1		
service	tools inventory	10	10	10			1	3		1		
work	cockpit	2	3	12			3	1		3		
work	meeting room	0	5	20			2	4		3		
work	work inventory	0	3	12			3	2		1		
work	workspace	0	5	20			3	2		2		

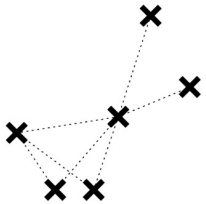
Computational design workflow



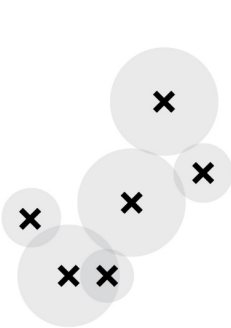
Programme of requirement



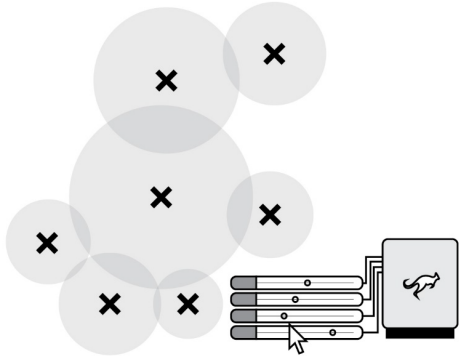
Assigning relative height



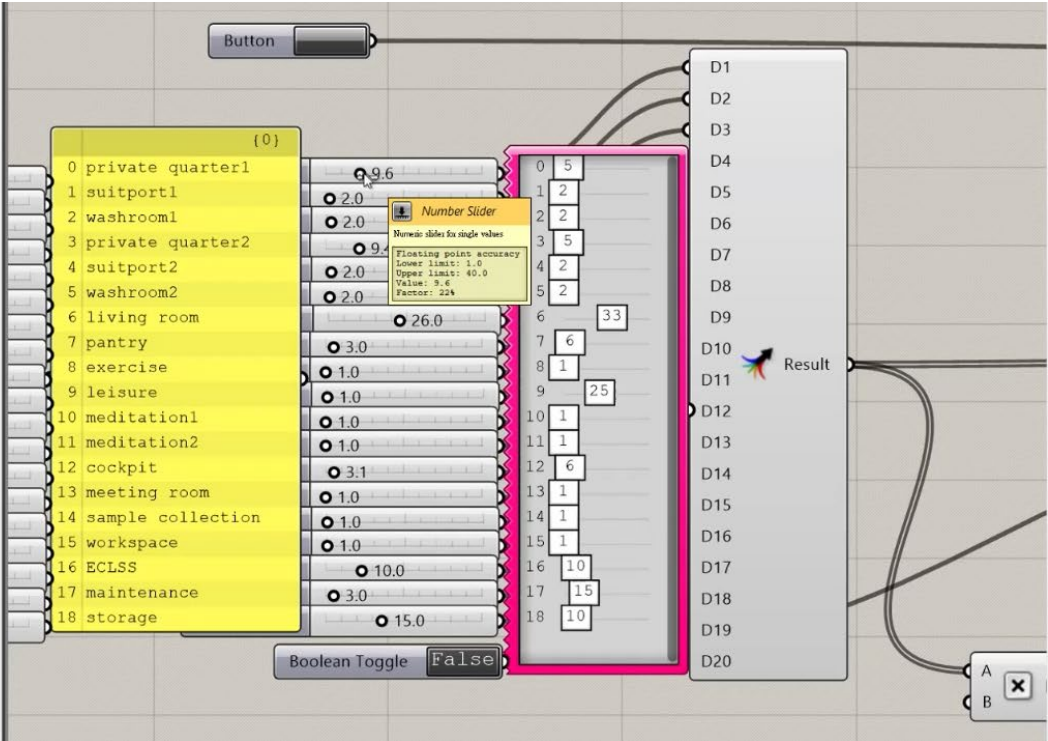
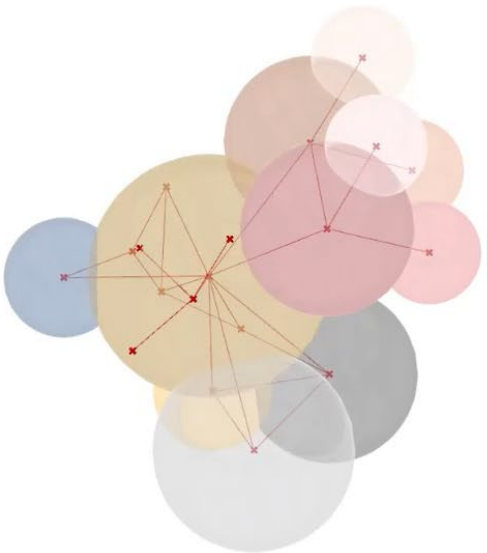
Resolving connections based on tasks routine



Assigning min. volumes

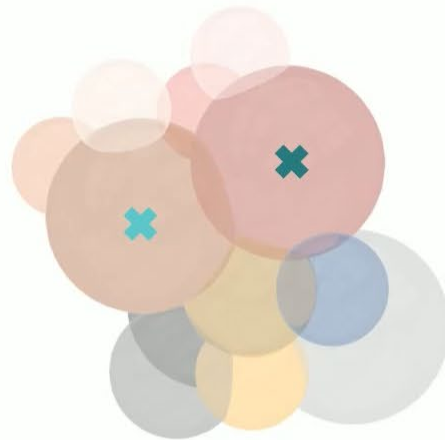


Adjust sliders to simulate and resolve changes over time

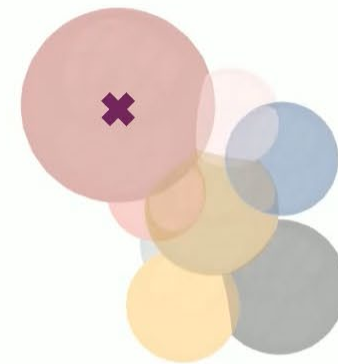




Engineering Support



Commander + Surveyor

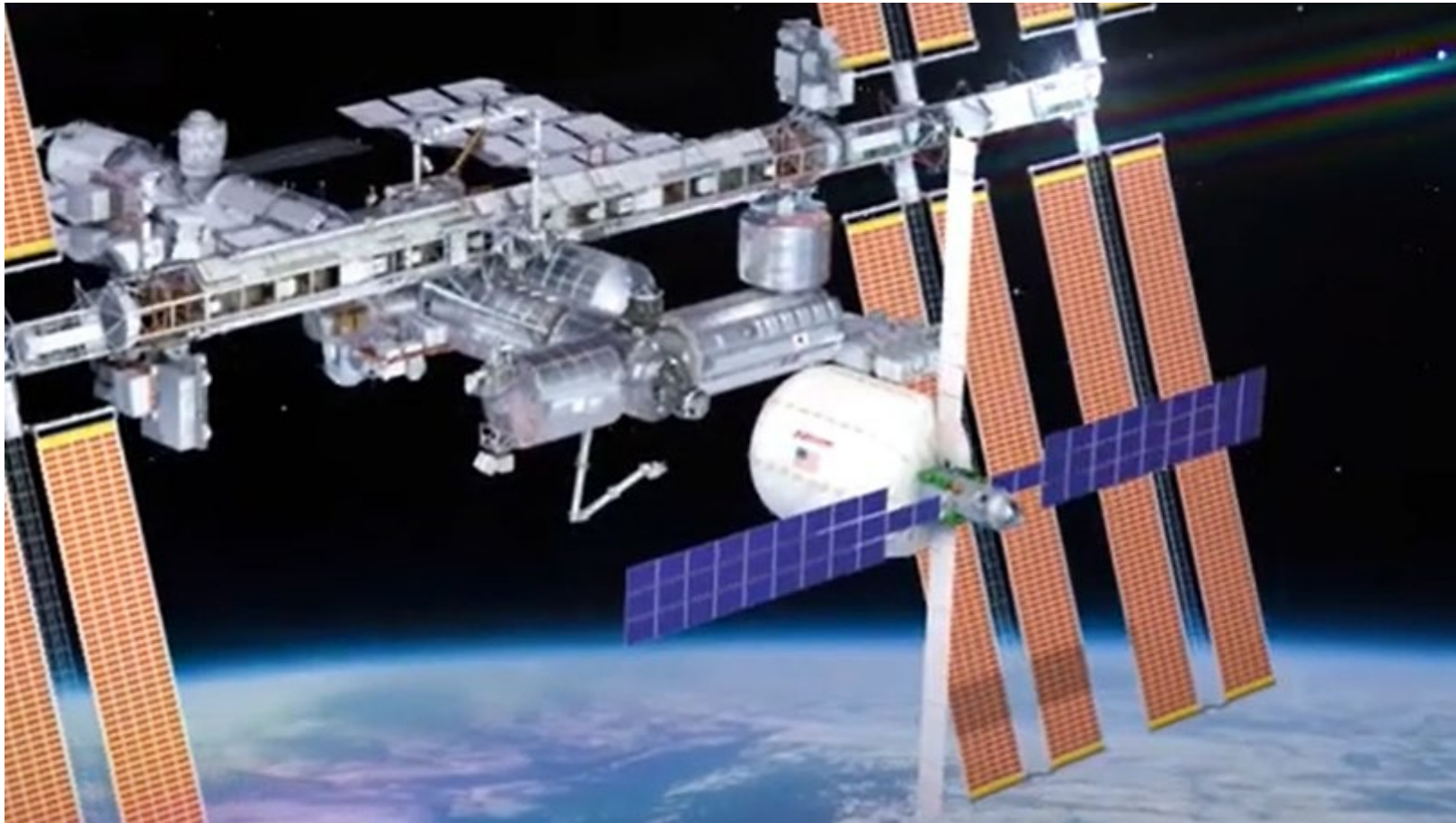


LTV Specialist

5. Implementation:

Proof of Concepts

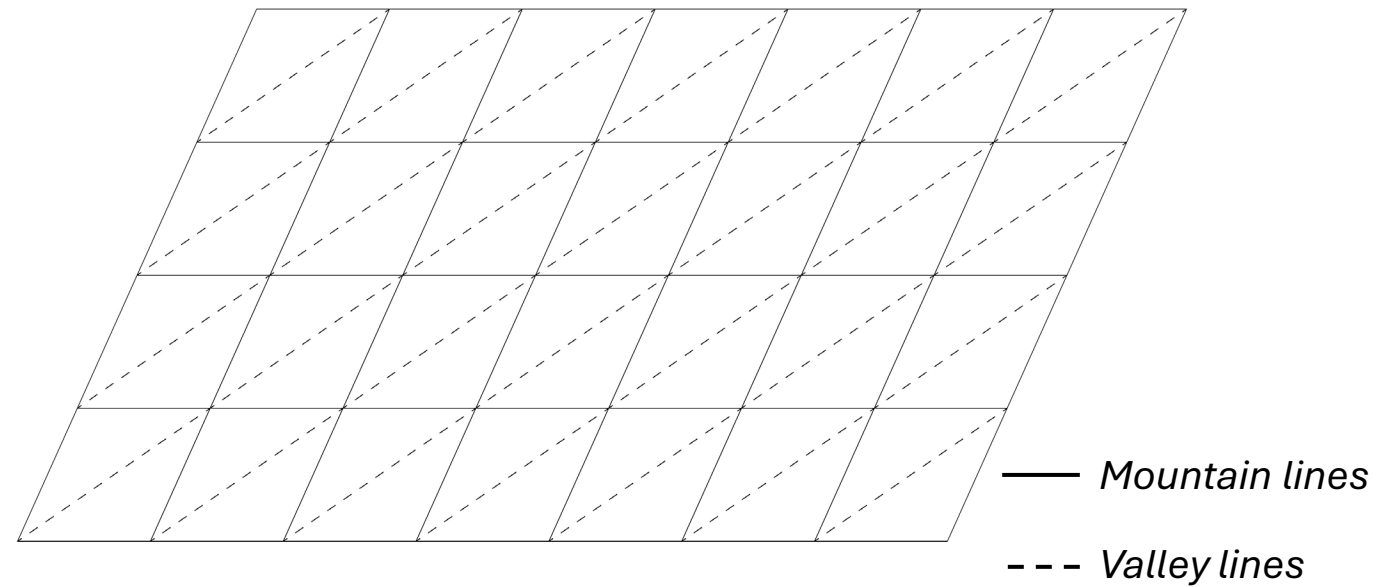
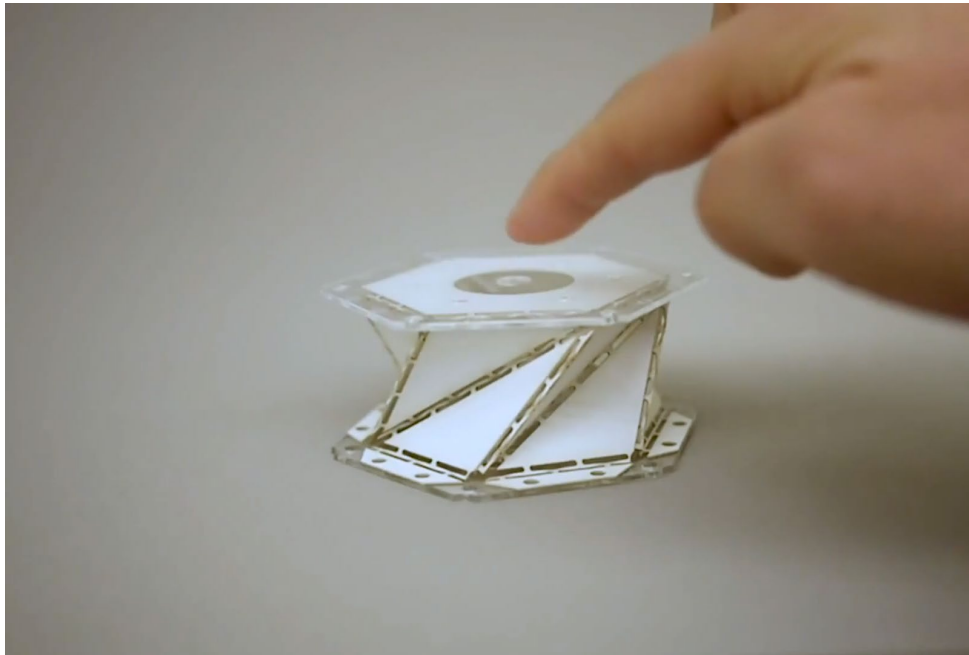
Inflatable Origami Structure



*Existing extraterrestrial inflatable habitat takes a **one-off** inflation transformation without considering deflation and thus reconfiguration.*

Origami-inspired material designed to soften impact

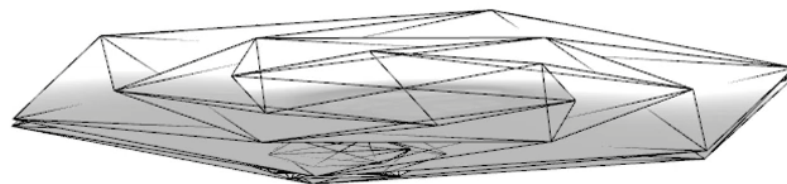
https://www.youtube.com/watch?v=jjt2lOjMdJ0&ab_channel=naturevideo



*The strength of origami structure is the capability to be expanded and **compressed**, and thus **reconfigured frequently**.*

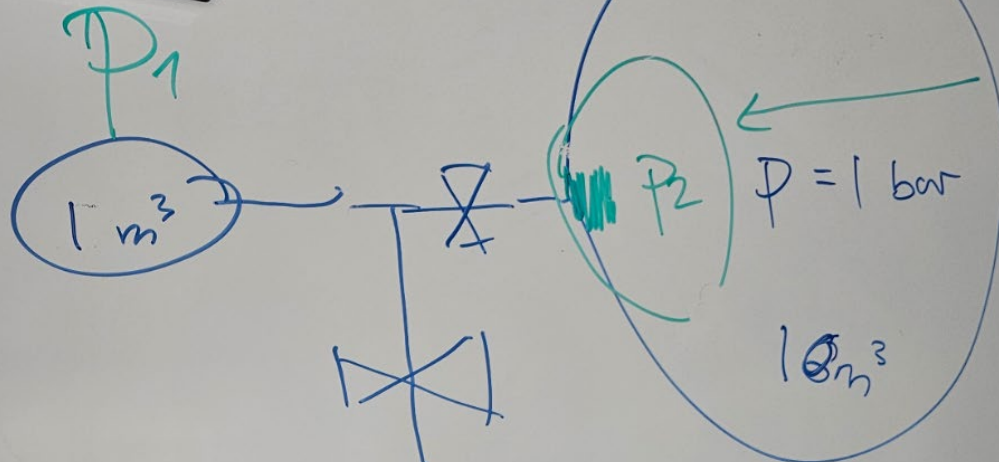


Pneumatic muscles to control shrinking and expanding of inflatable structure



inflated main volume

Space deflation transformation process



$$\frac{P_1}{P_2} = \frac{V_2}{V_1}$$

$$\frac{5000}{14.7} = \frac{P_1}{P_2} \approx 300$$

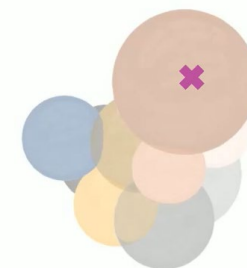
Challenge with pressure

Due to lack of atmosphere in the outer space

→ Air pressure in the lunar environment ~ 0

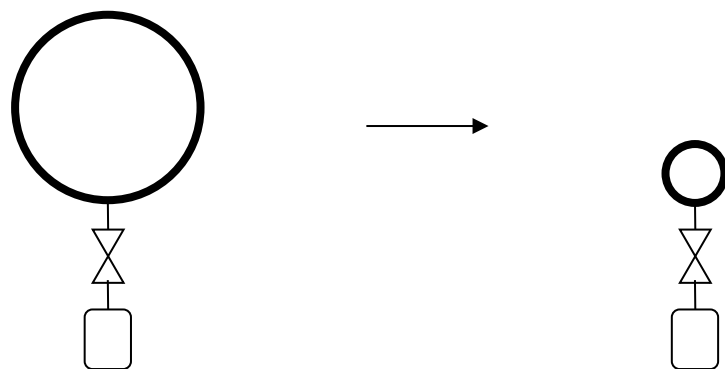
→ High pressure difference between exterior and interior

→ Large amount of force needed for compressing to zero



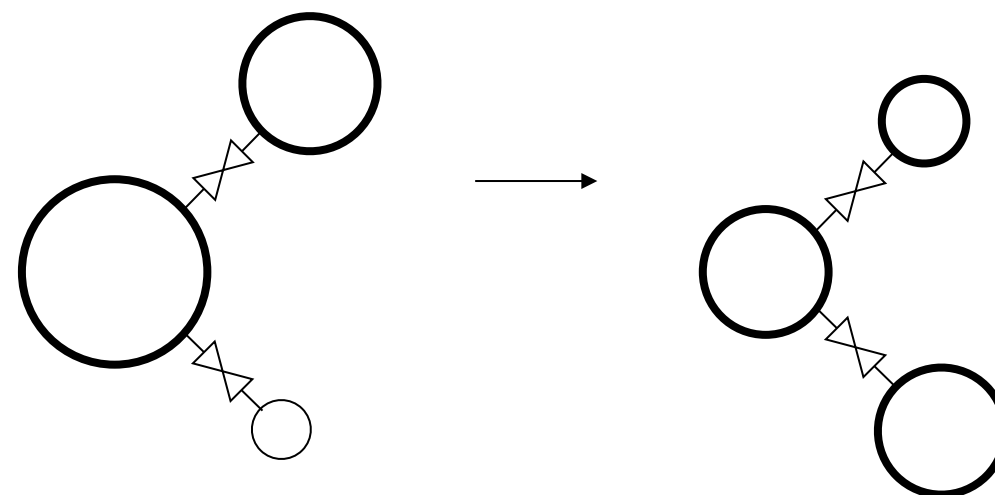
Solution 1:

Use of strong air compressor with high energy consumption



Solution 2:

Reconfiguration by transferring air from one volume to another, instead of frequent complete deflation



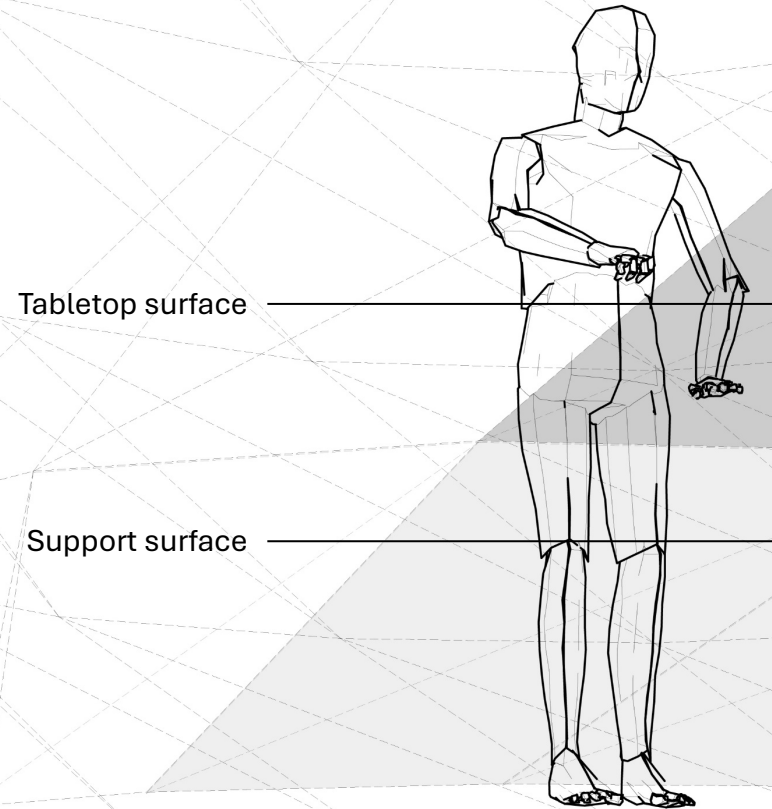
Reconfiguration Strategy

Reconfiguration Strategy 1 (surface)



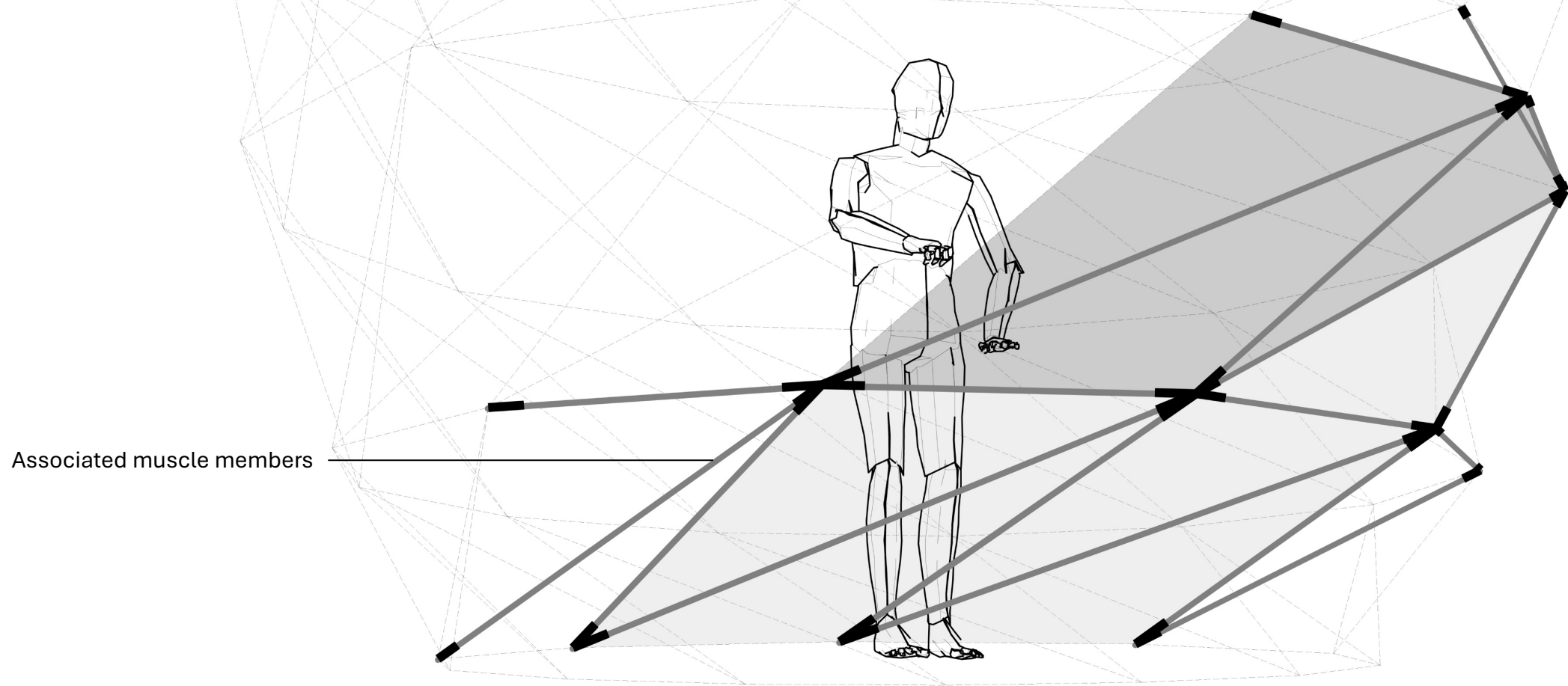
Furniture surface transformation process

Reconfiguration Strategy 1 (surface)



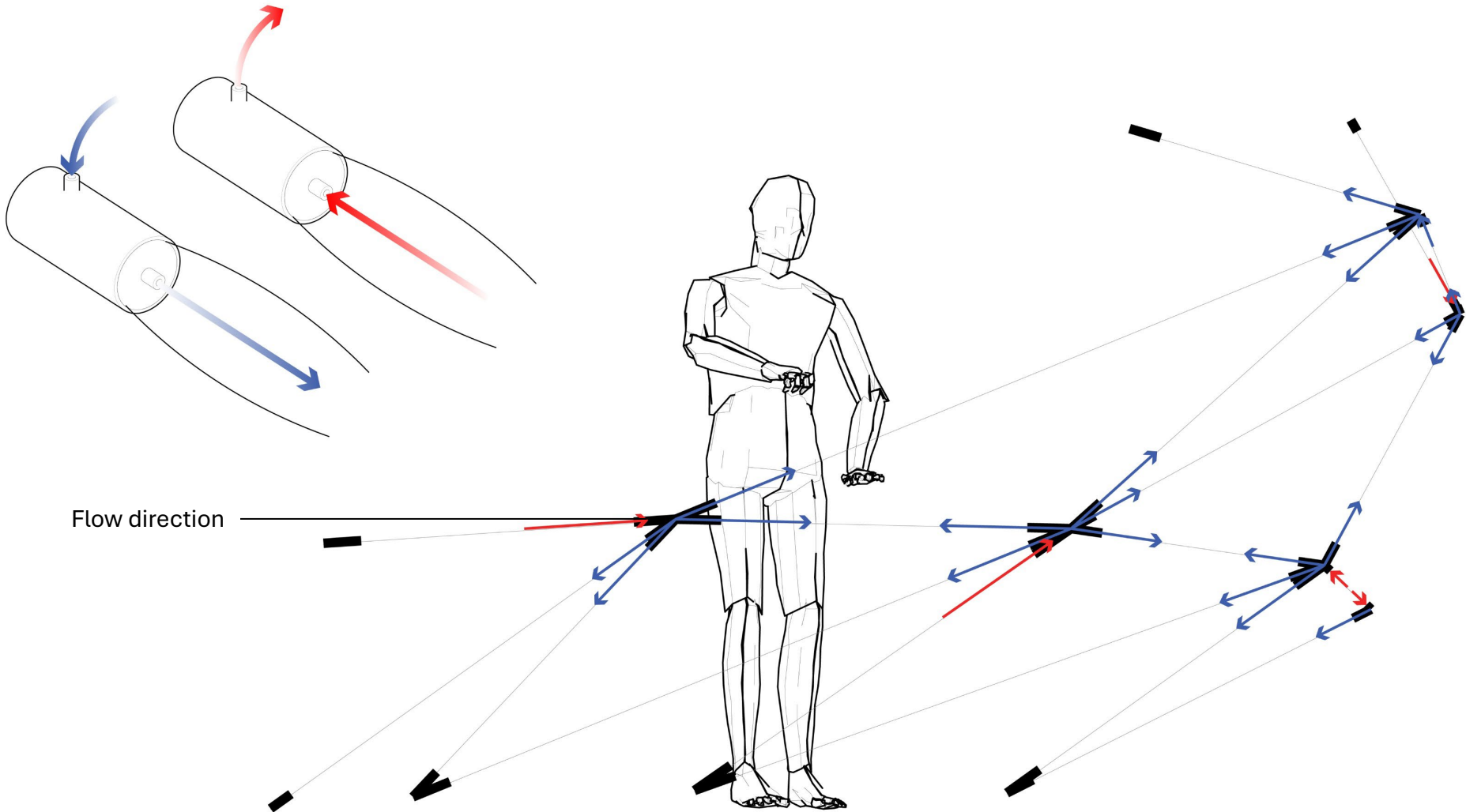
Furniture surface transformation process

Reconfiguration Strategy 1 (surface)



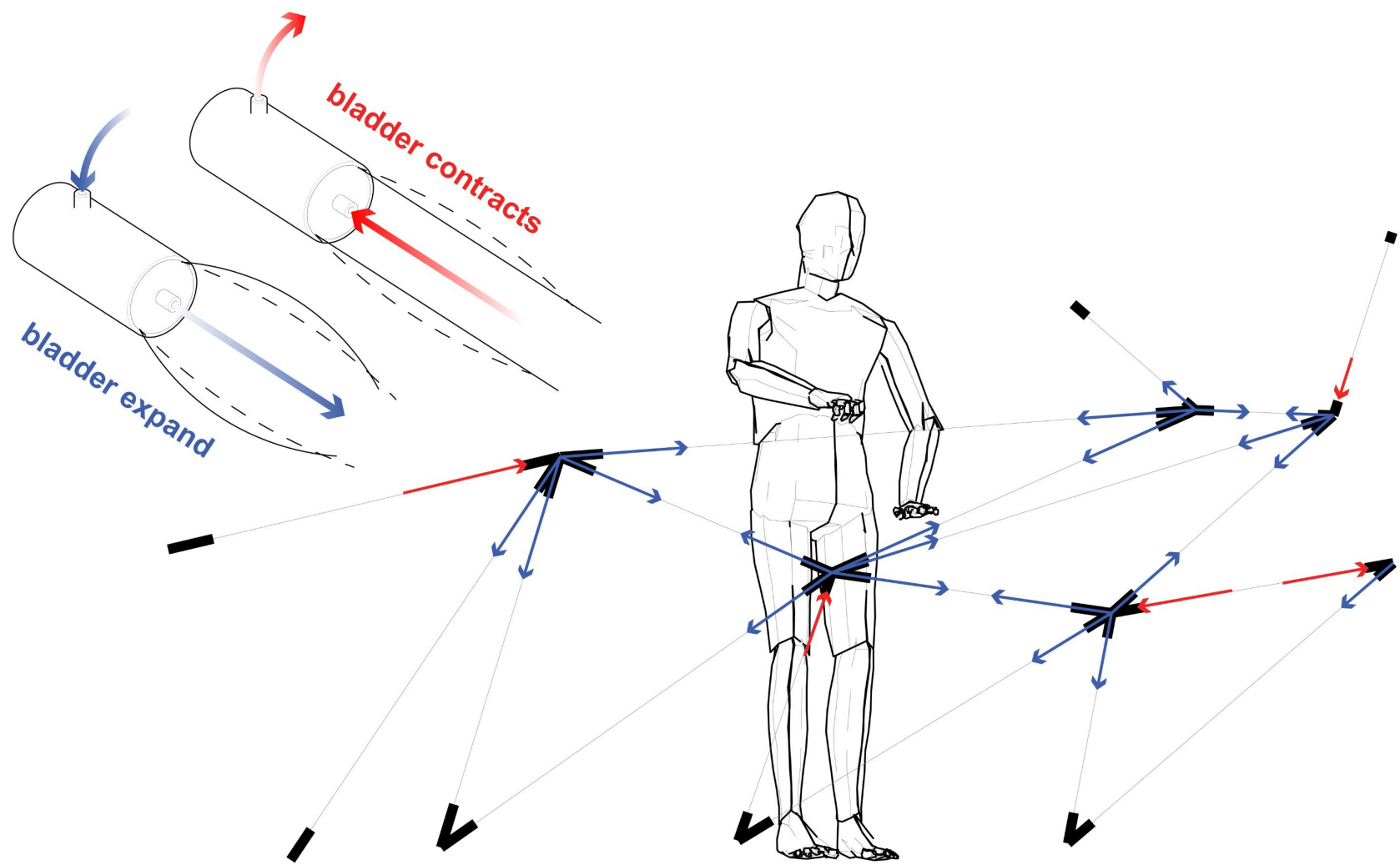
Furniture surface transformation process

Reconfiguration Strategy 1 (surface)



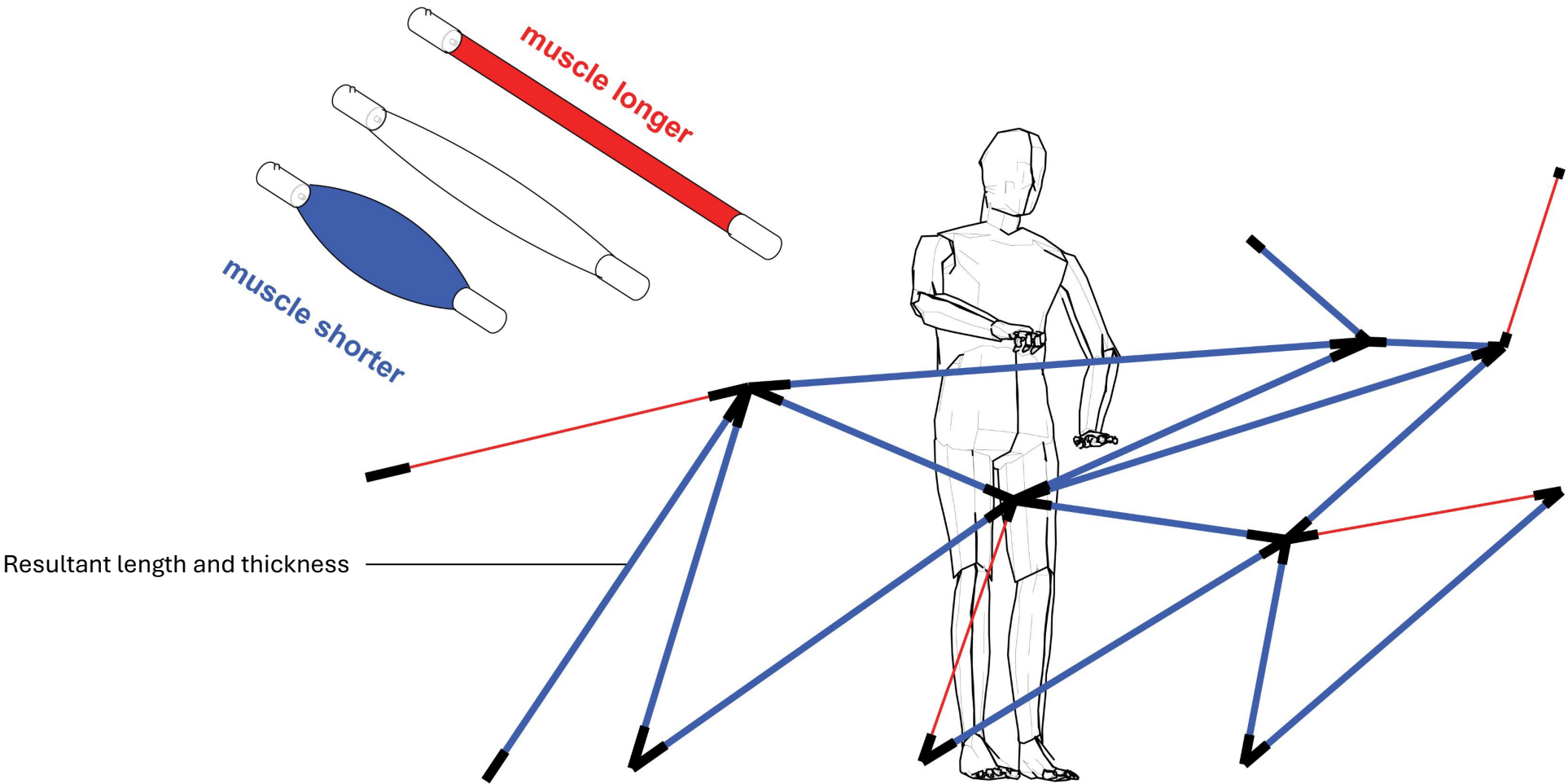
Furniture surface transformation process

Reconfiguration Strategy 1 (surface)



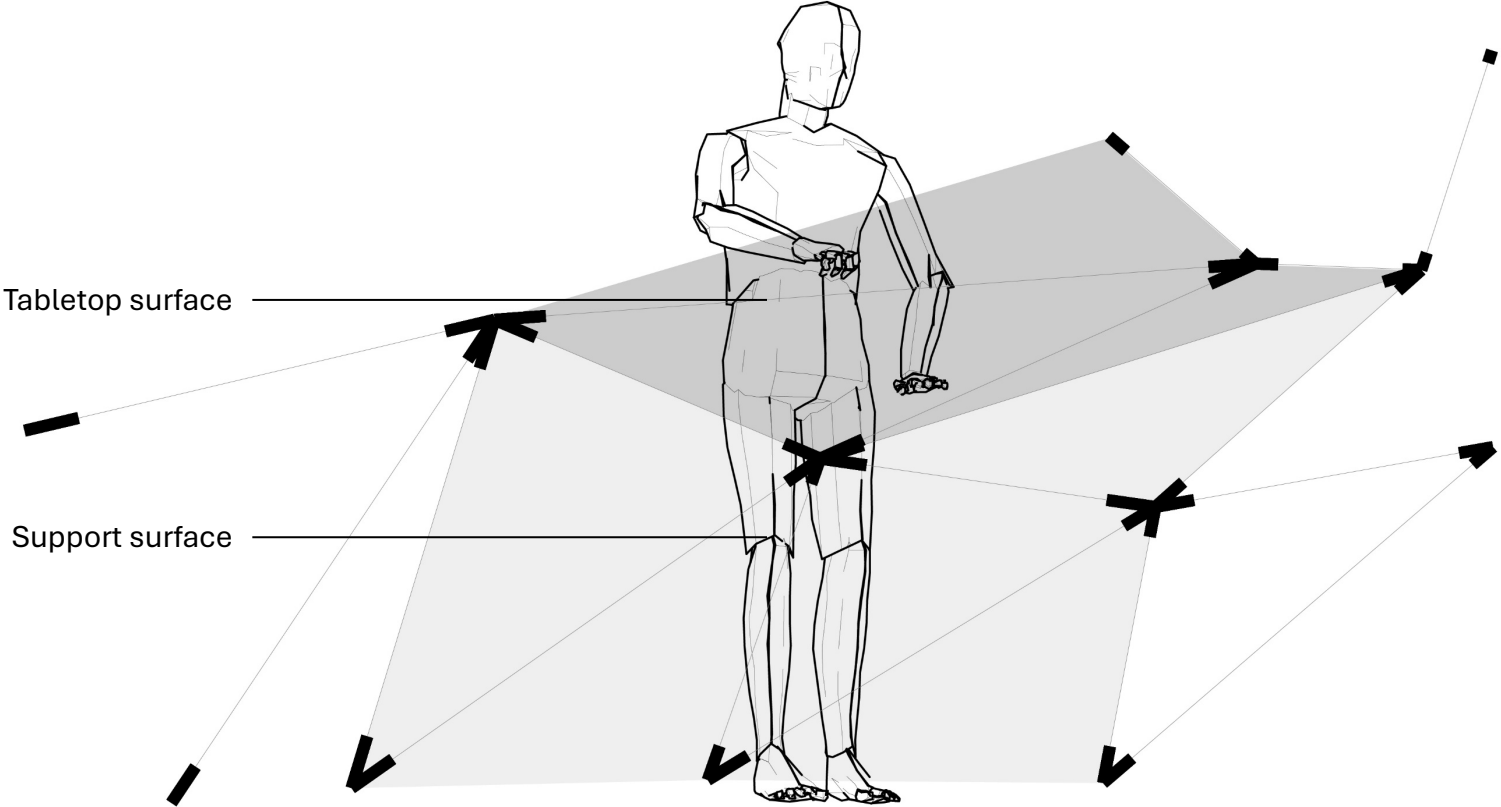
Furniture surface transformation process

Reconfiguration Strategy 1 (surface)



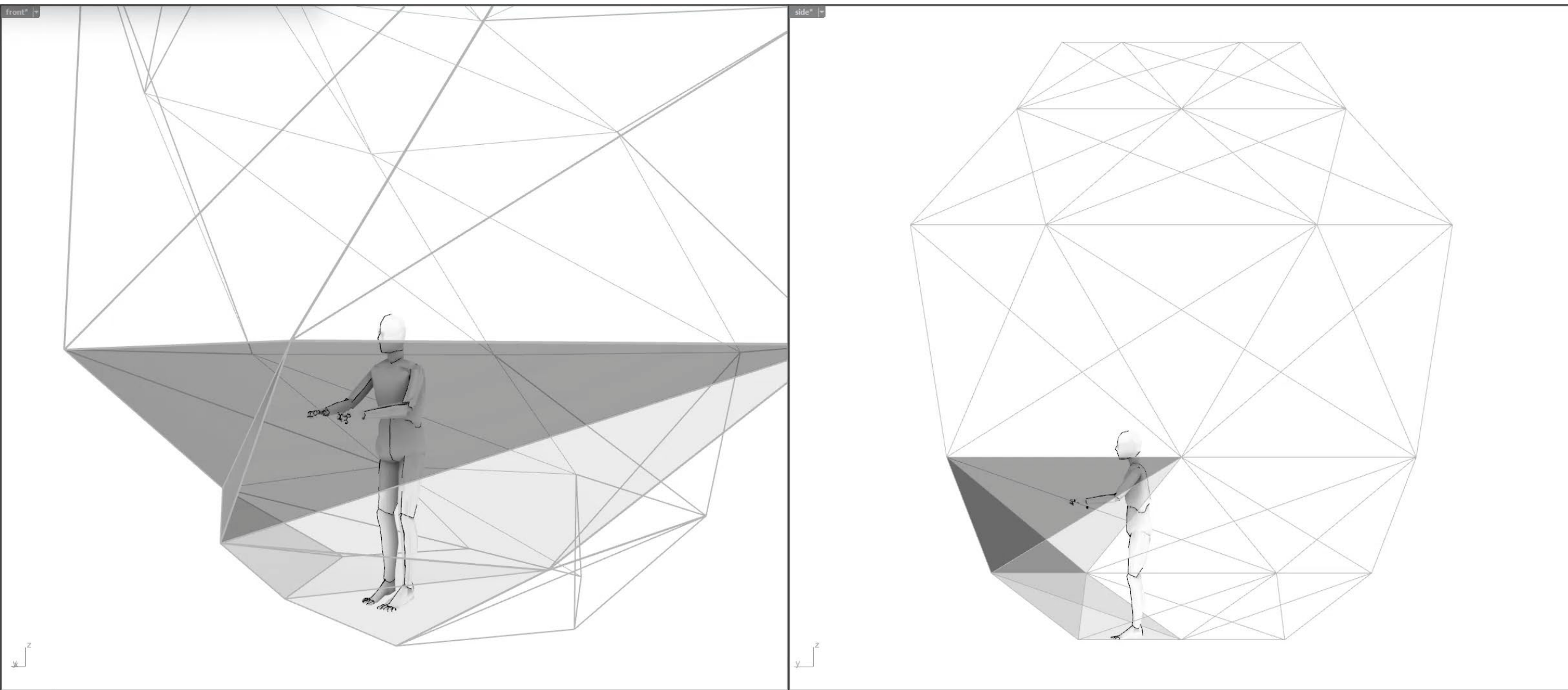
Furniture surface transformation process

Reconfiguration Strategy 1 (surface)



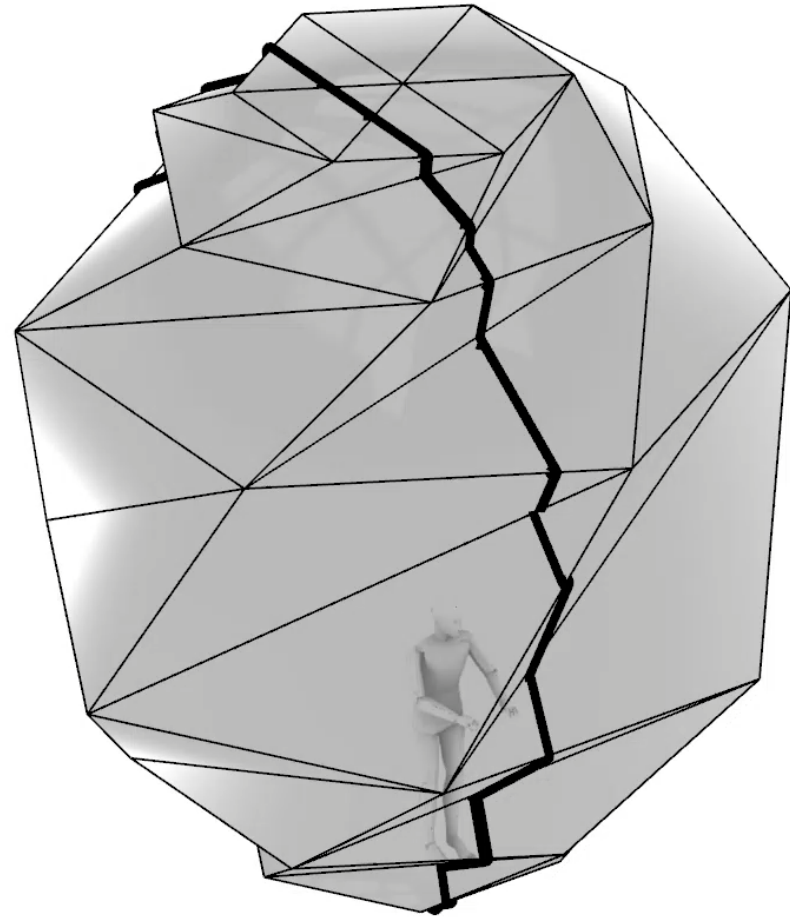
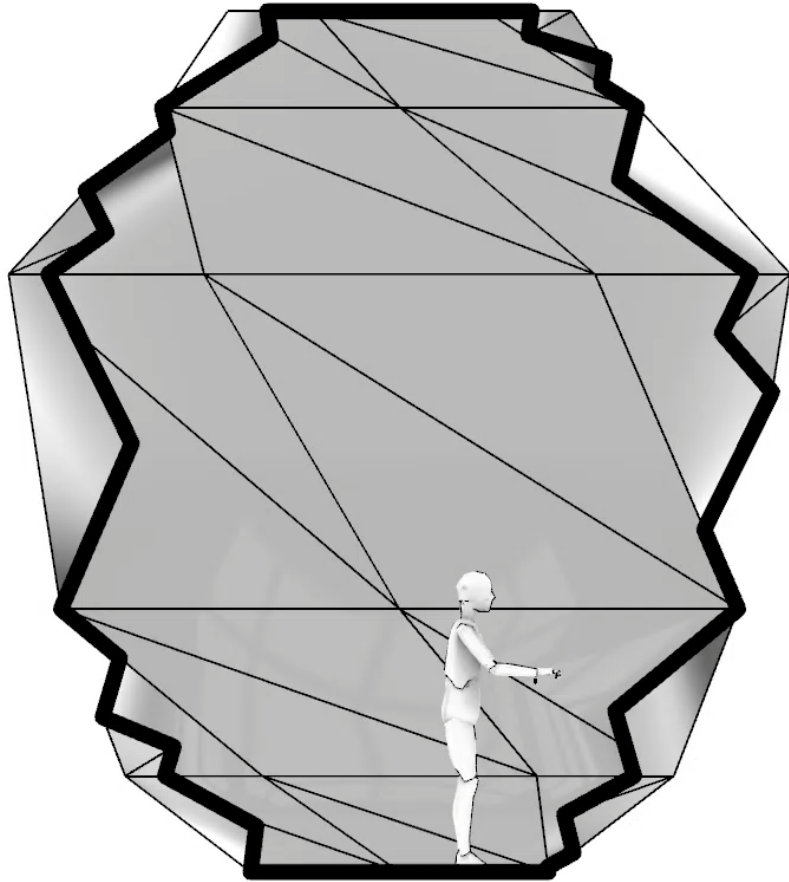
Furniture surface transformation process

Reconfiguration Strategy 1 (surface)



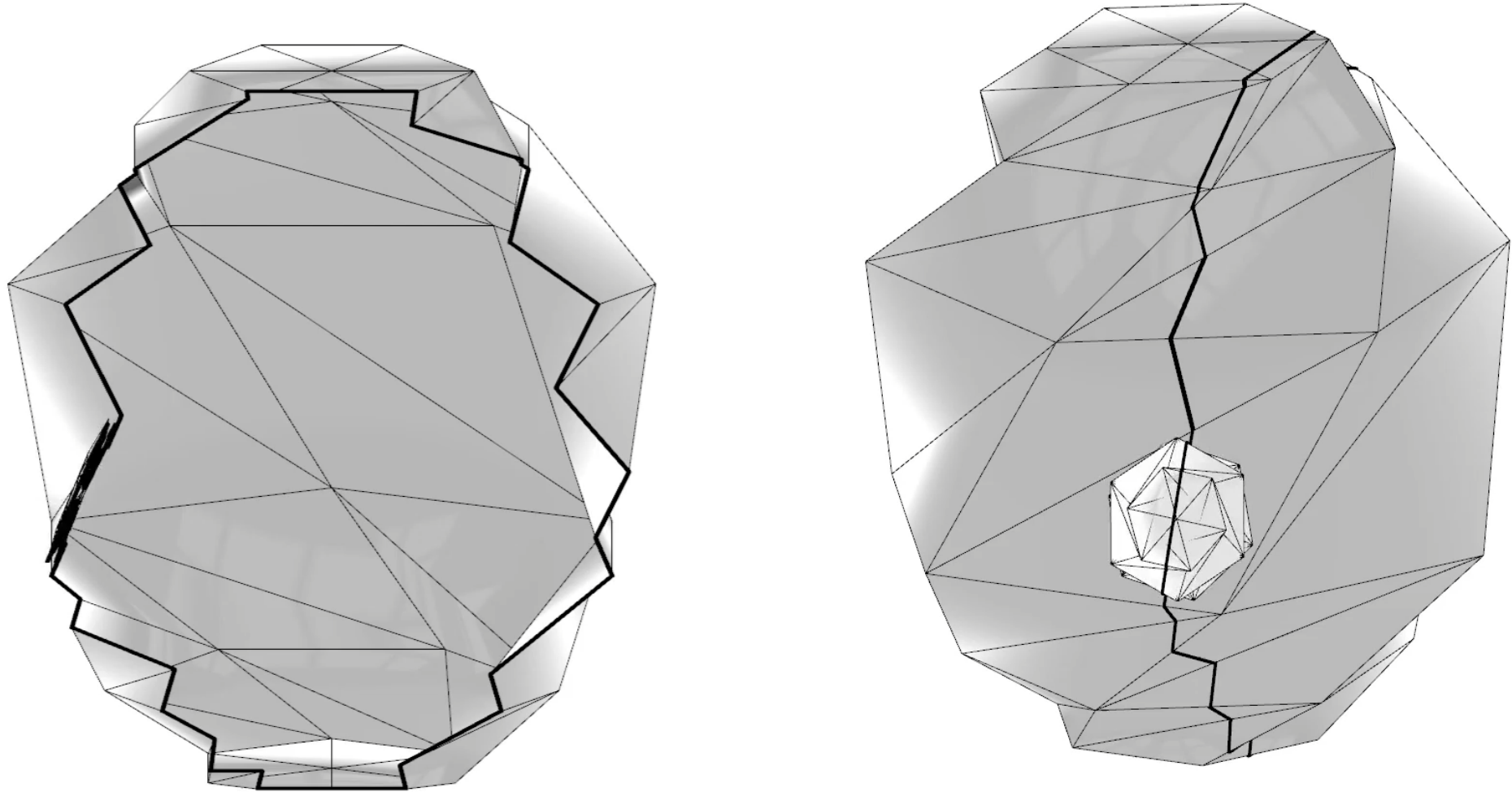
Furniture surface transformation process

Reconfiguration Strategy 1 (surface)



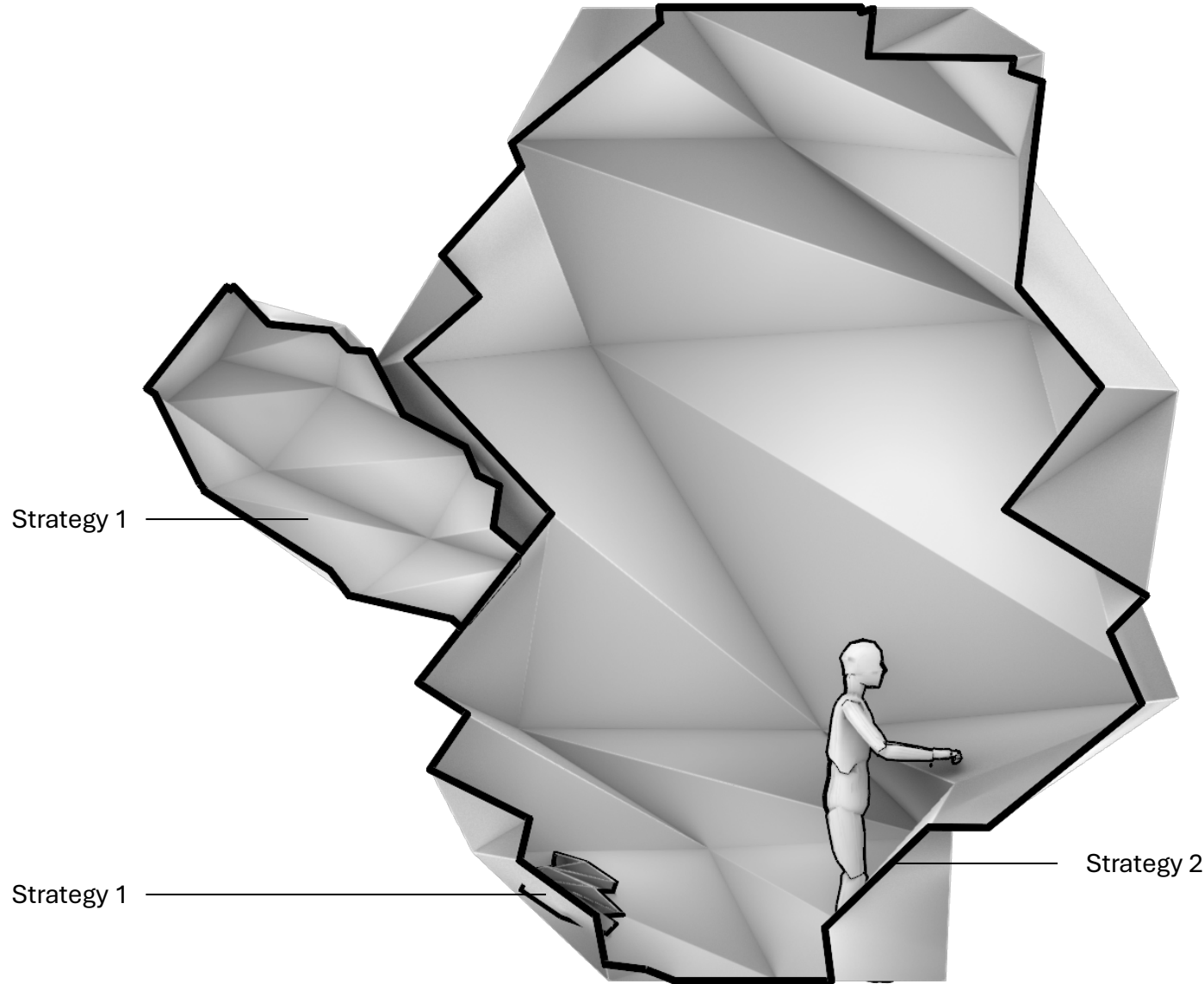
Furniture surface transformation process

Reconfiguration Strategy 2 (volume)



Space deflation transformation process

Section Overview



Strategy 1

- Larger volume can be created
- Limited by prefabricated membrane

Strategy 2

- More flexibility
- Cannot create larger volume

Furniture surface transformation process

Sensor

Sensor System Overview

On envelope

Air quality sensor

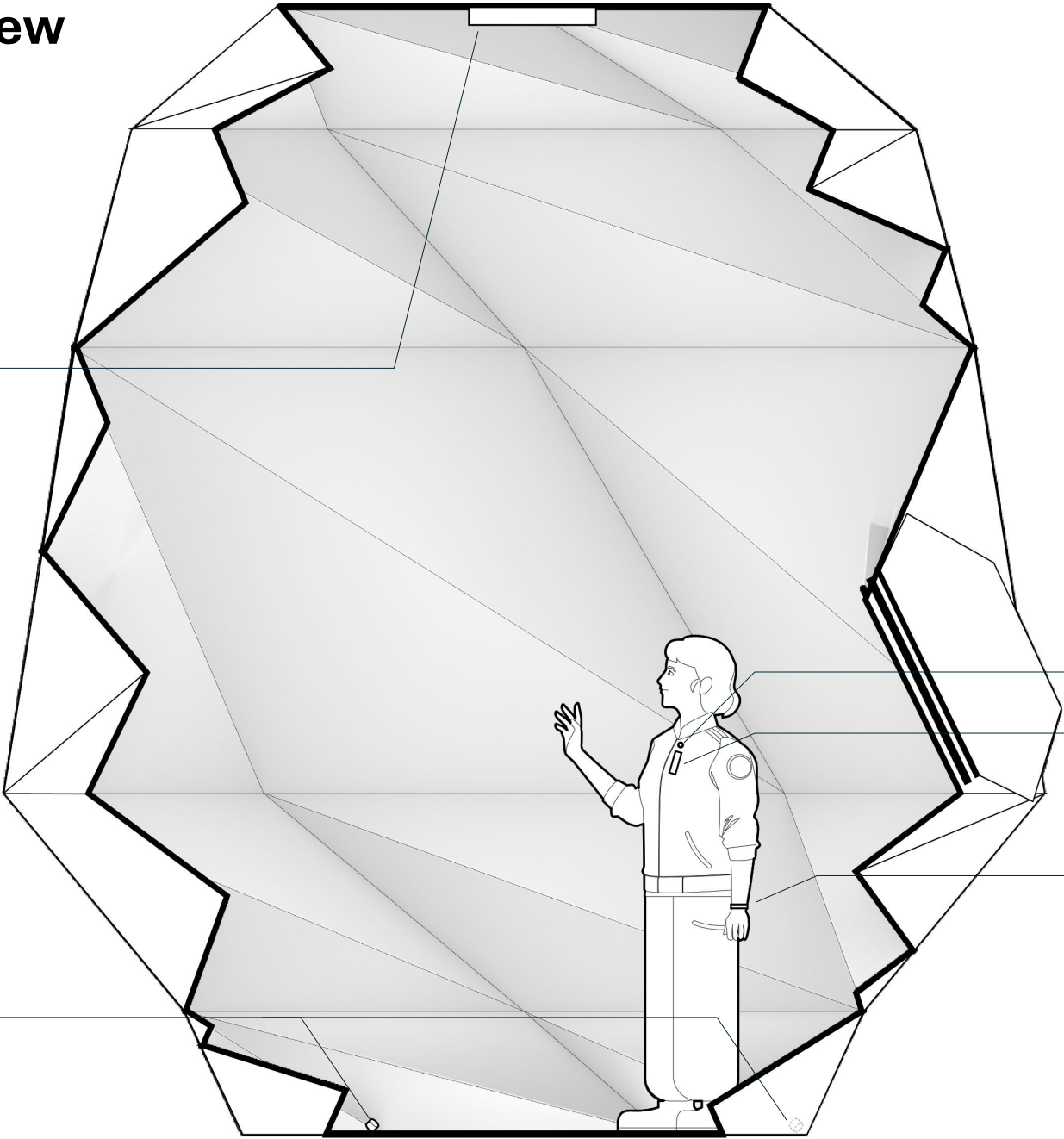
LiDAR scanner

On wearables

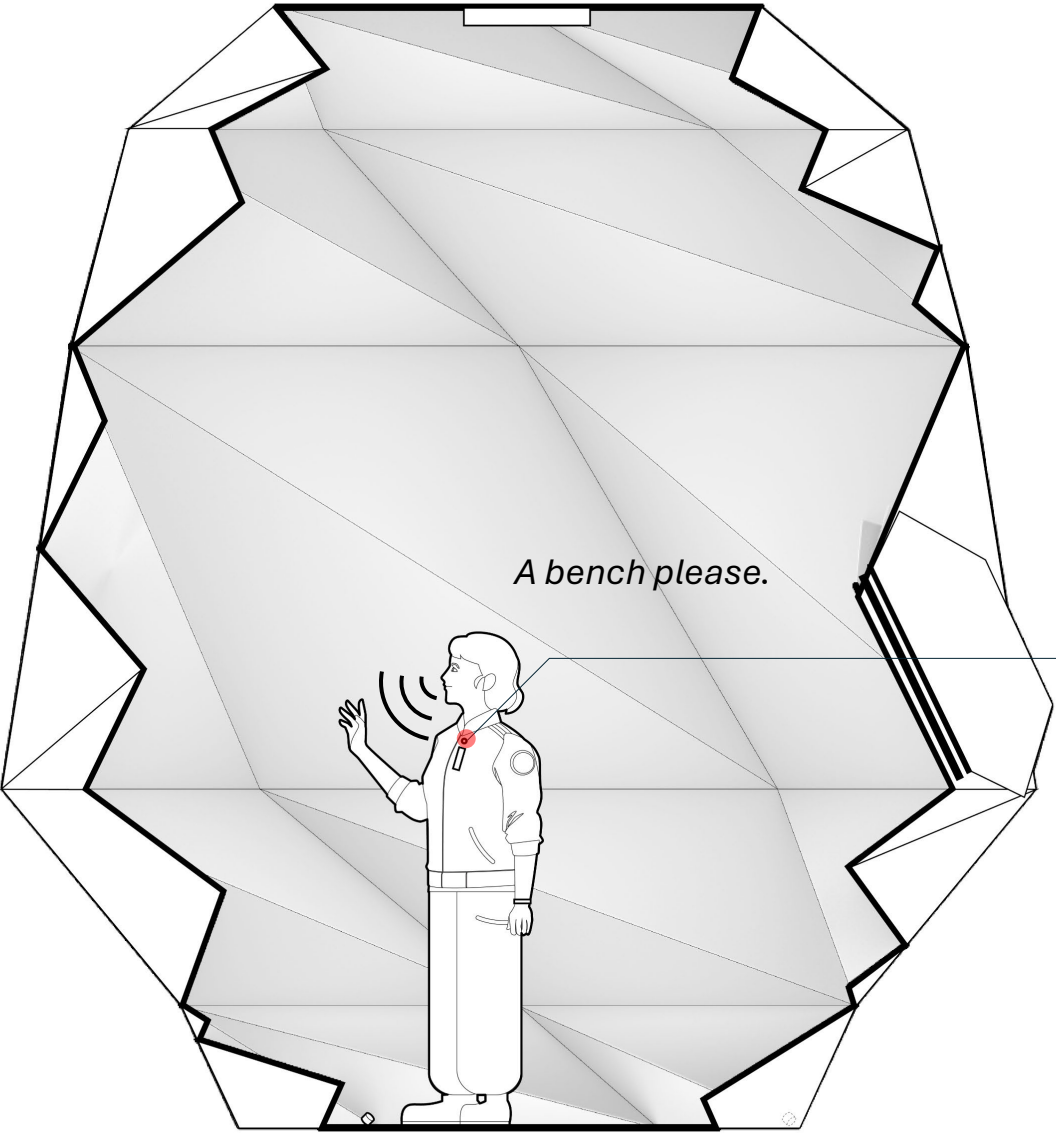
Microphone

Body temperature sensor

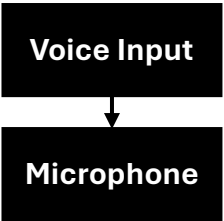
Pulse rate sensor



Scenario 1: Table Transformation

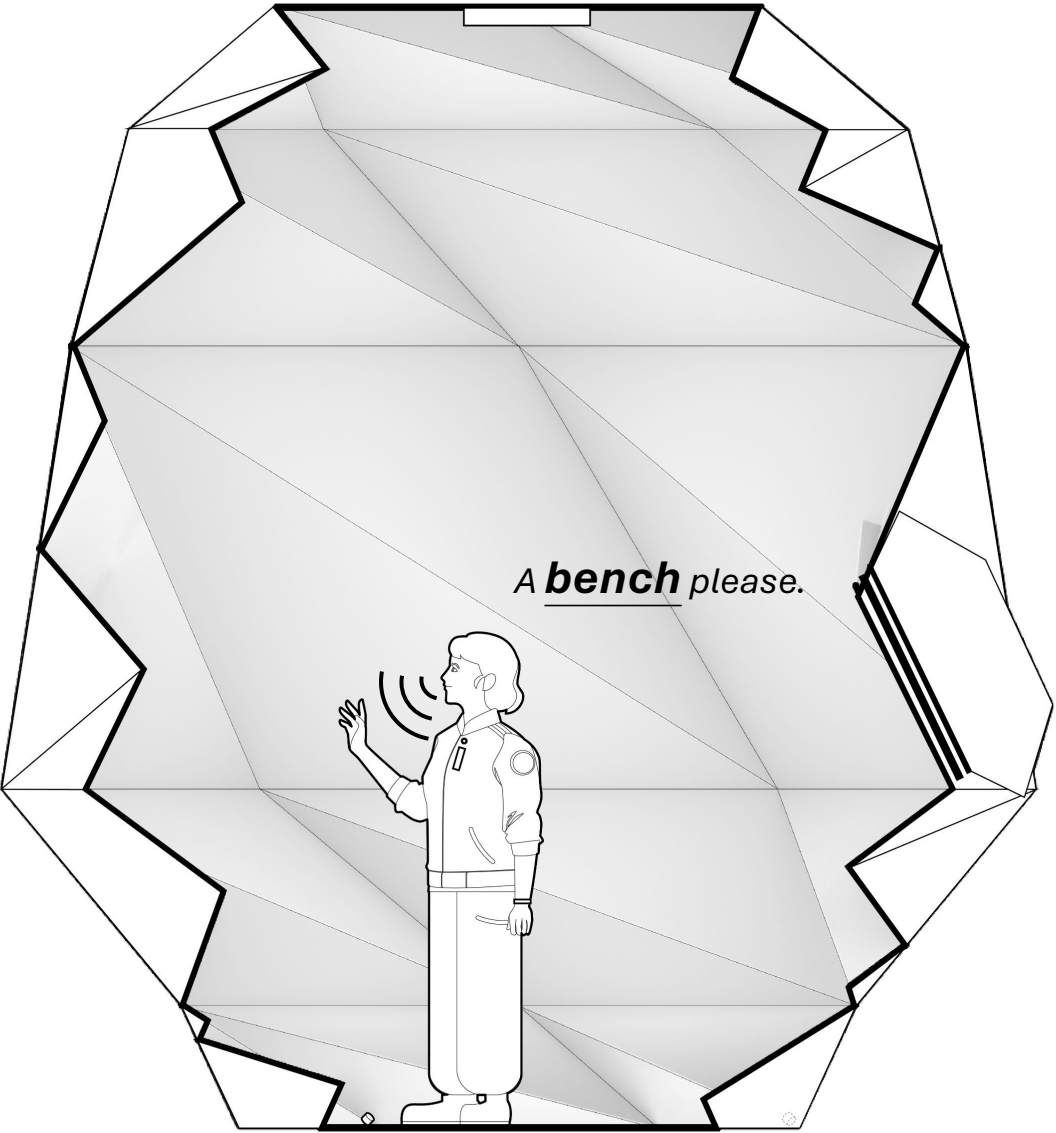


1. What action to be taken?

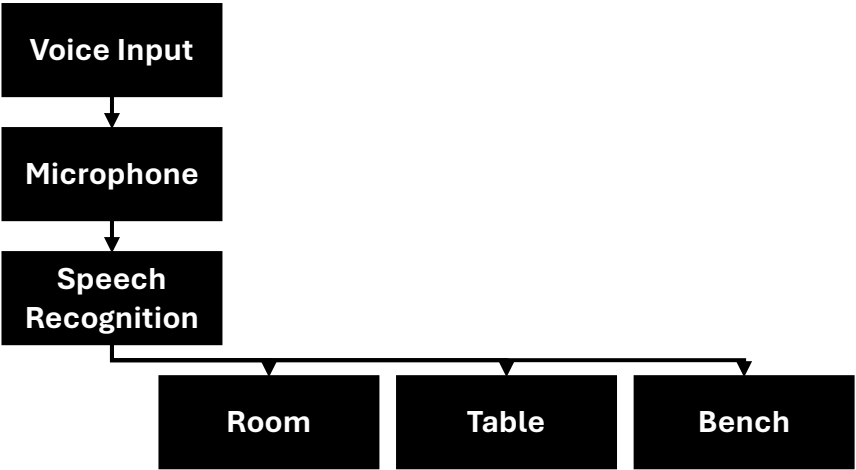


Microphone

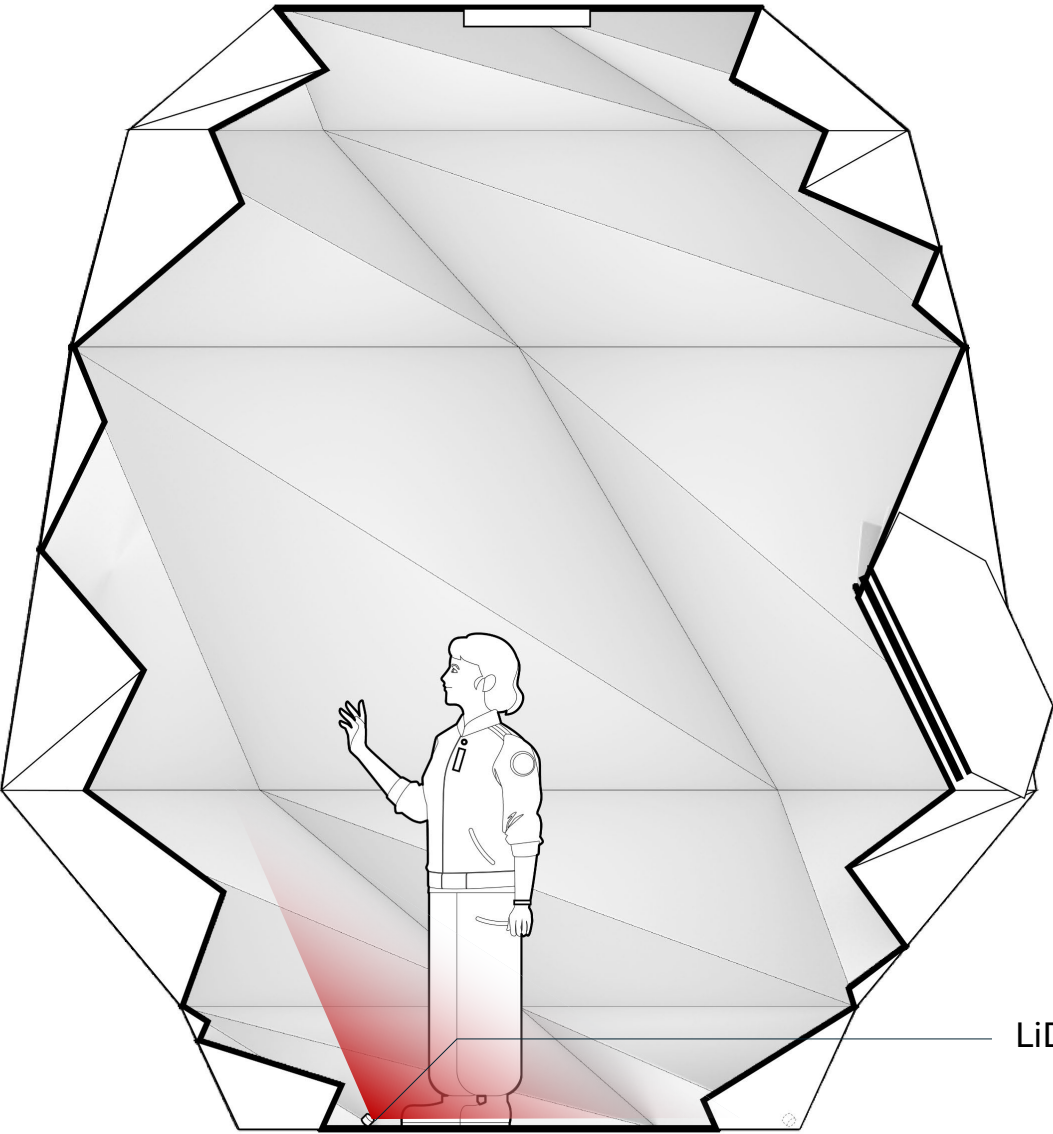
Scenario 1: Table Transformation



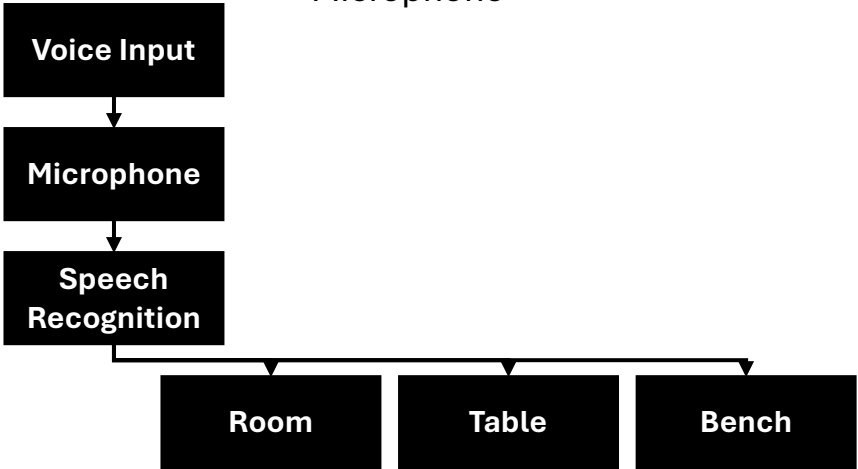
1. What action to be taken?



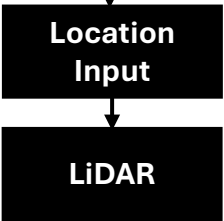
Scenario 1: Table Transformation



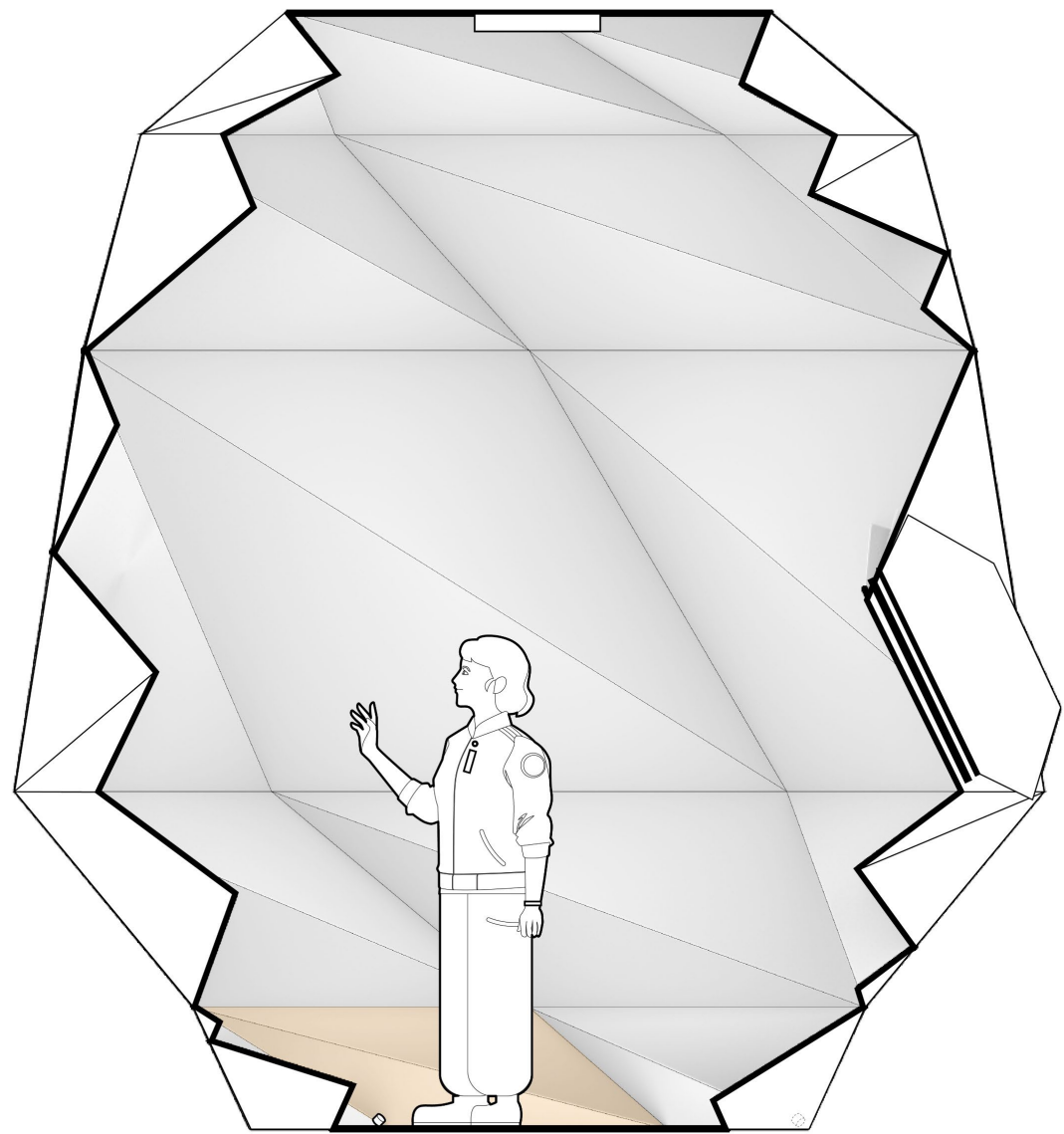
1. What action to be taken?
Microphone



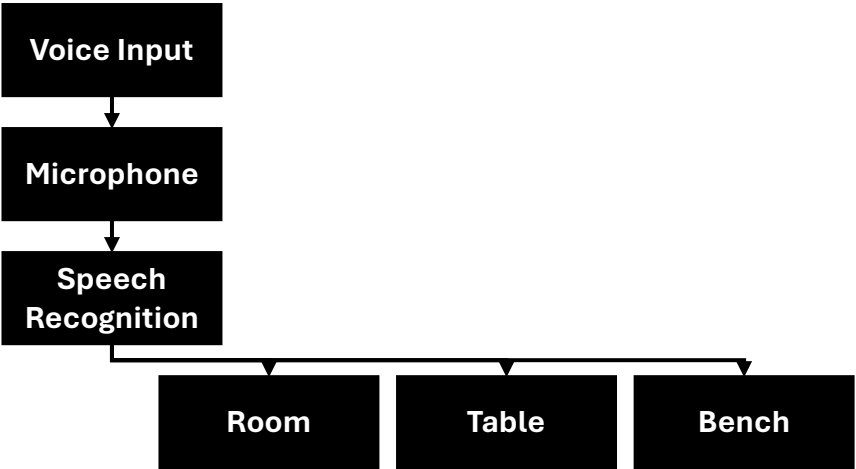
2. Where exactly does it take place?



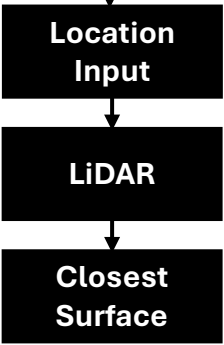
Scenario 1: Table Transformation



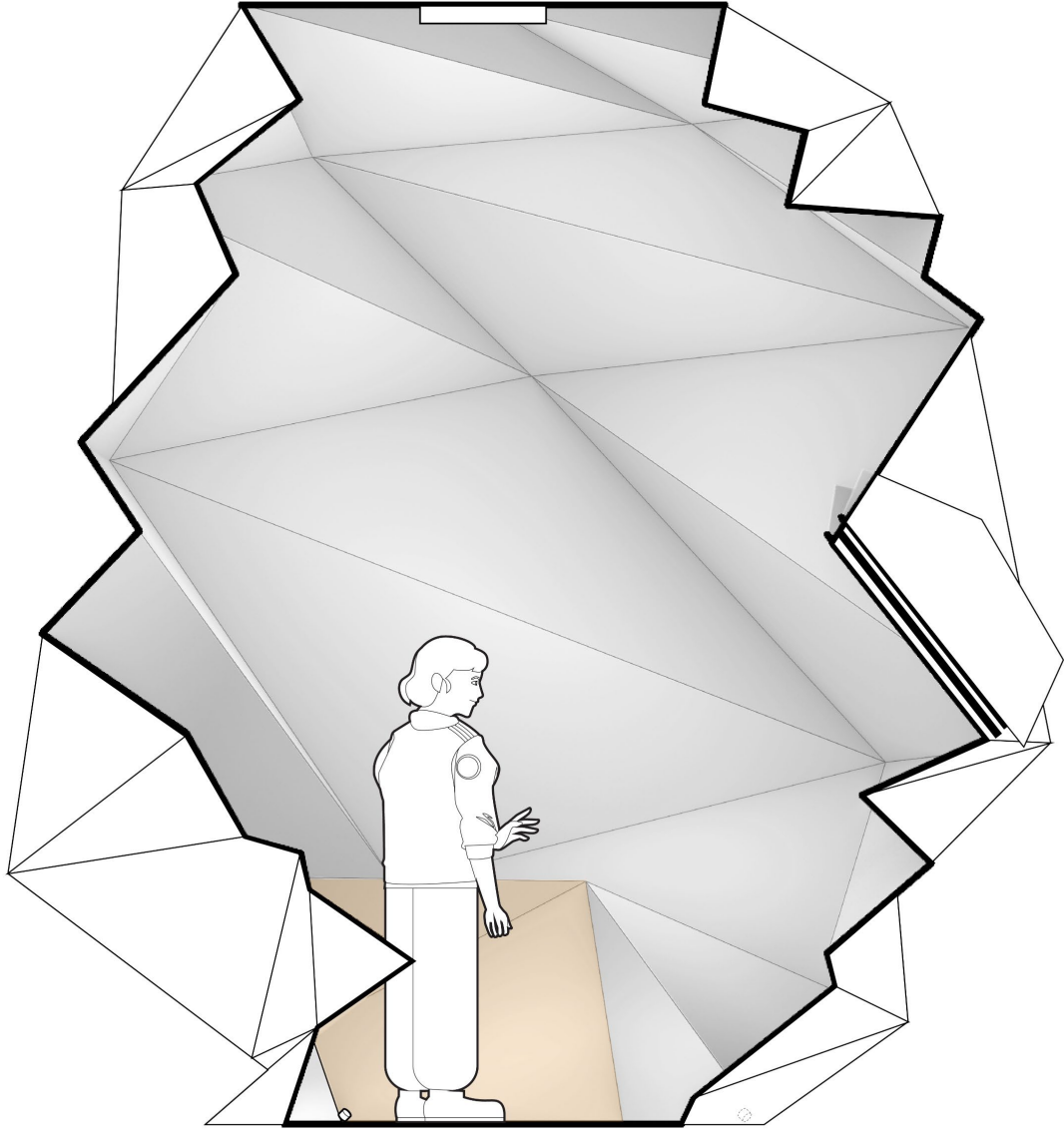
1. What action to be taken?



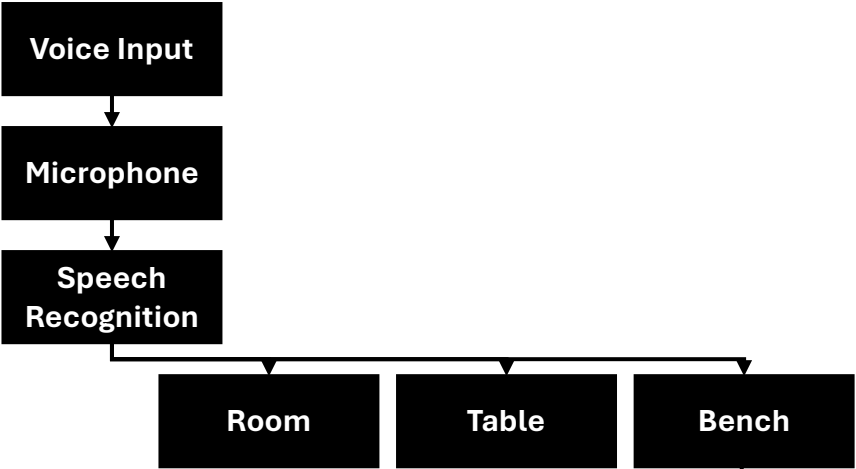
2. Where exactly does it take place?



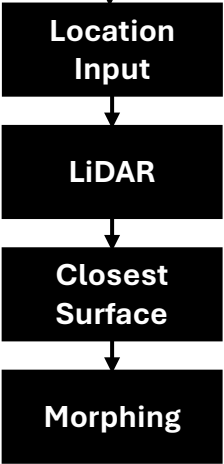
Scenario 1: Table Transformation



1. What action to be taken?

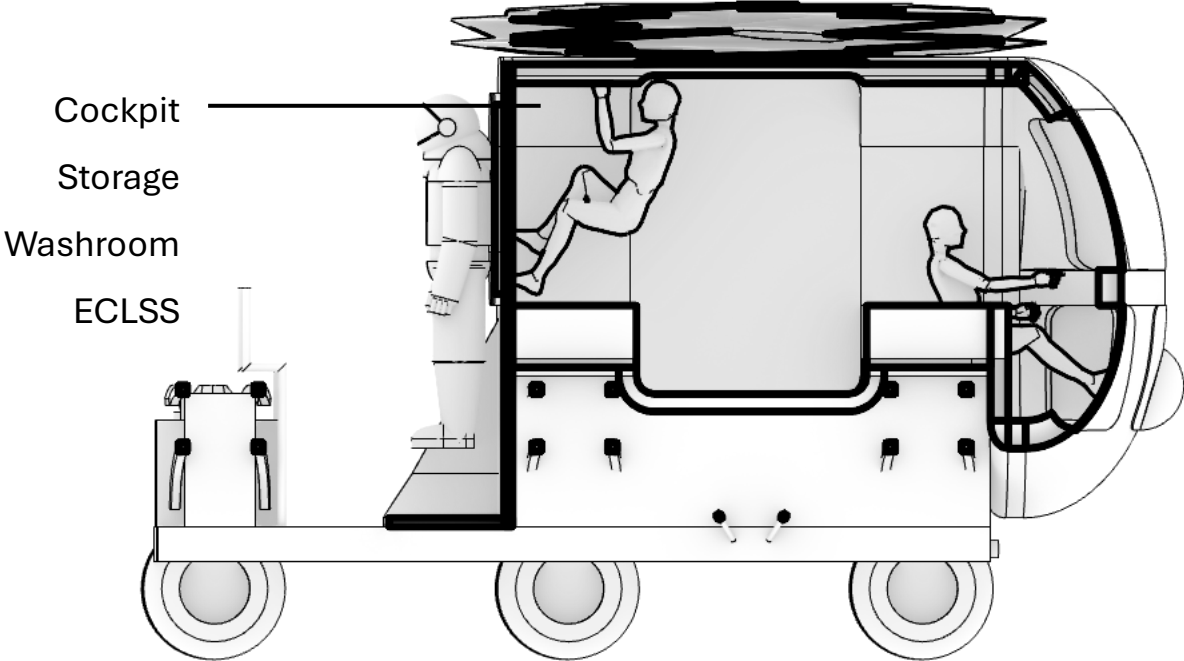


2. Where exactly does it take place?

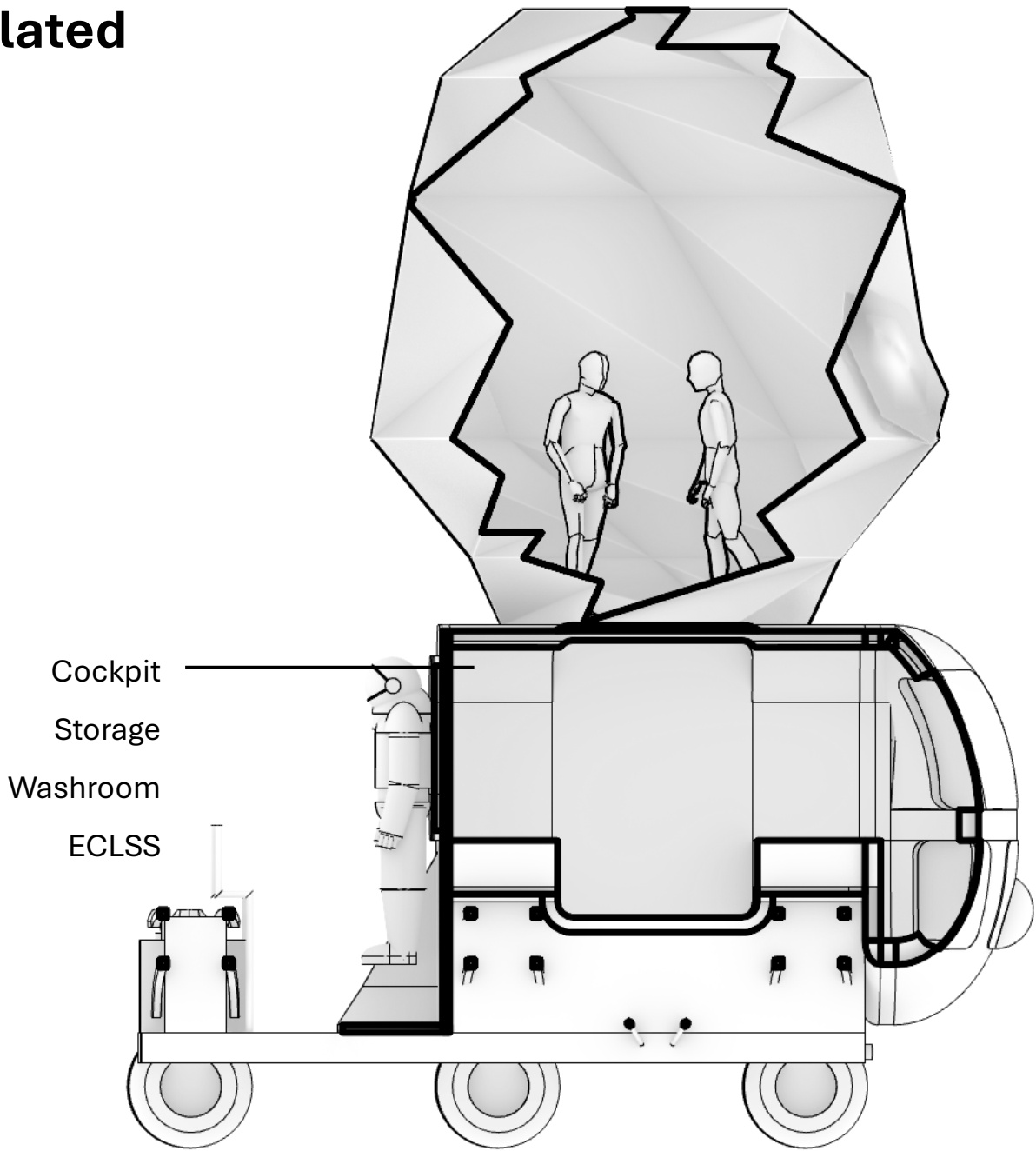


Scenarios

Deflated



Inflated



Meal Preparation/Leisure

Degree of social interaction: 3

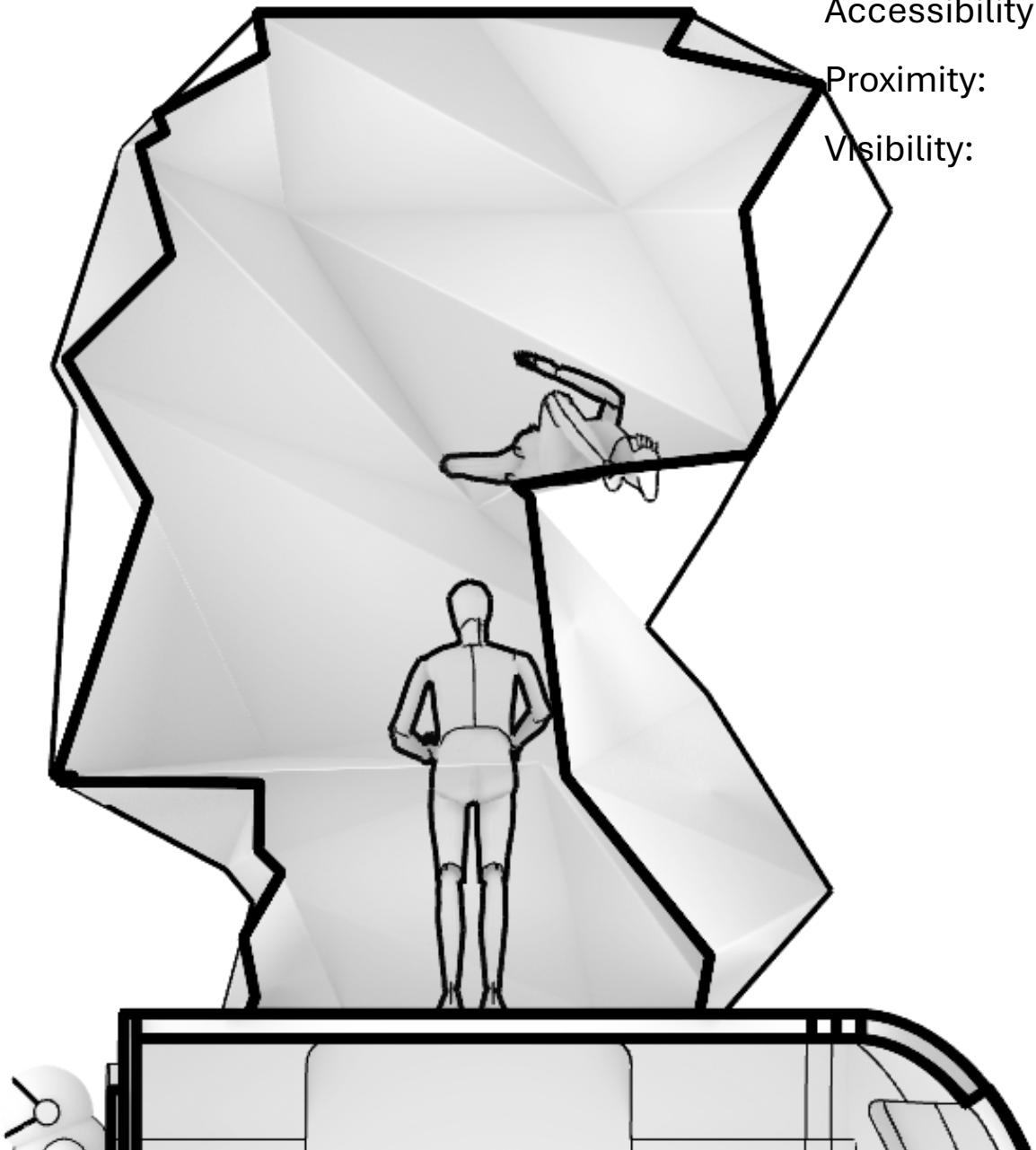
Accessibility:



Proximity:



Visibility:



Sleeping

Degree of social interaction: 1

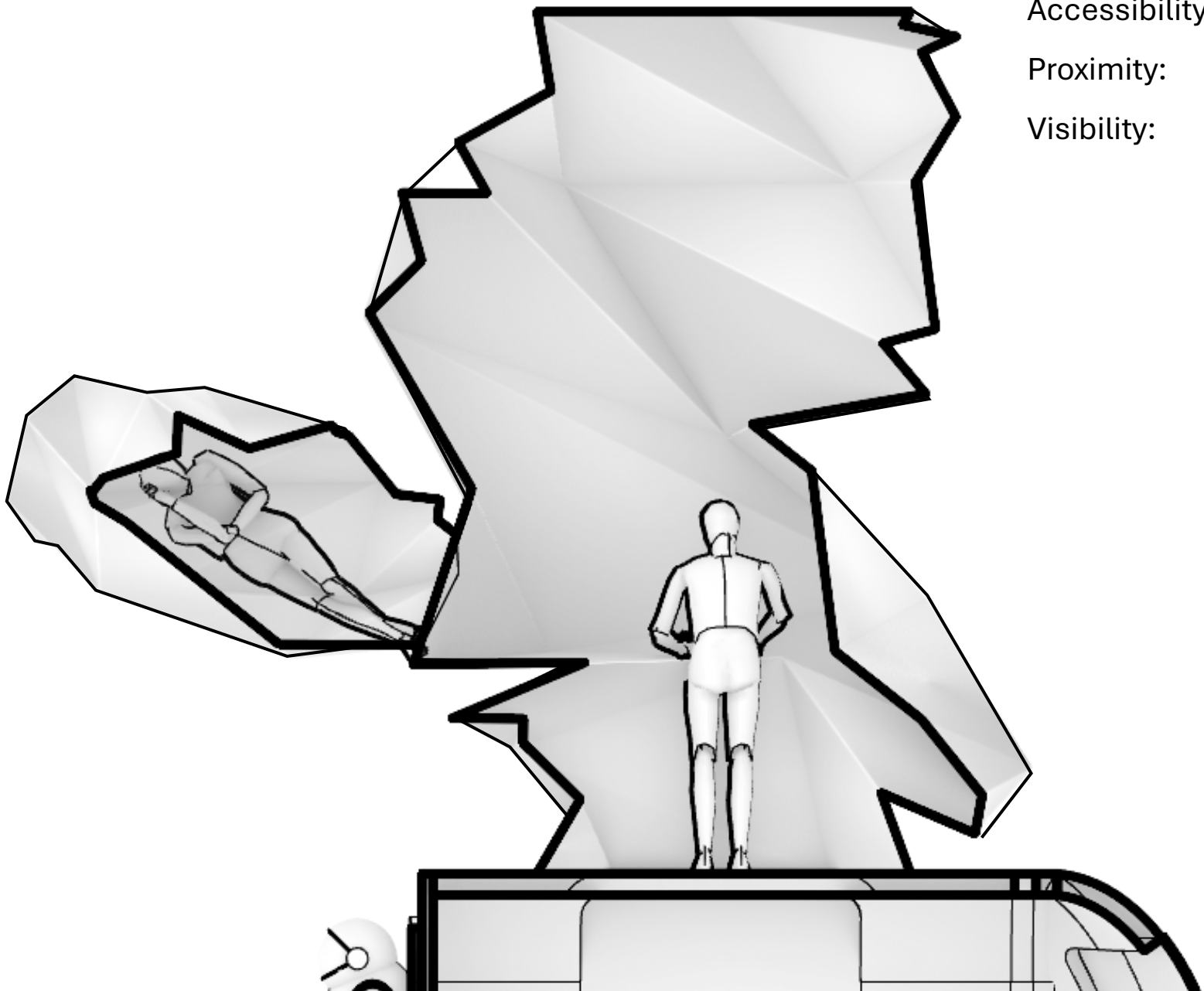
Accessibility:



Proximity:



Visibility:



Sleeping

Degree of social interaction: 1

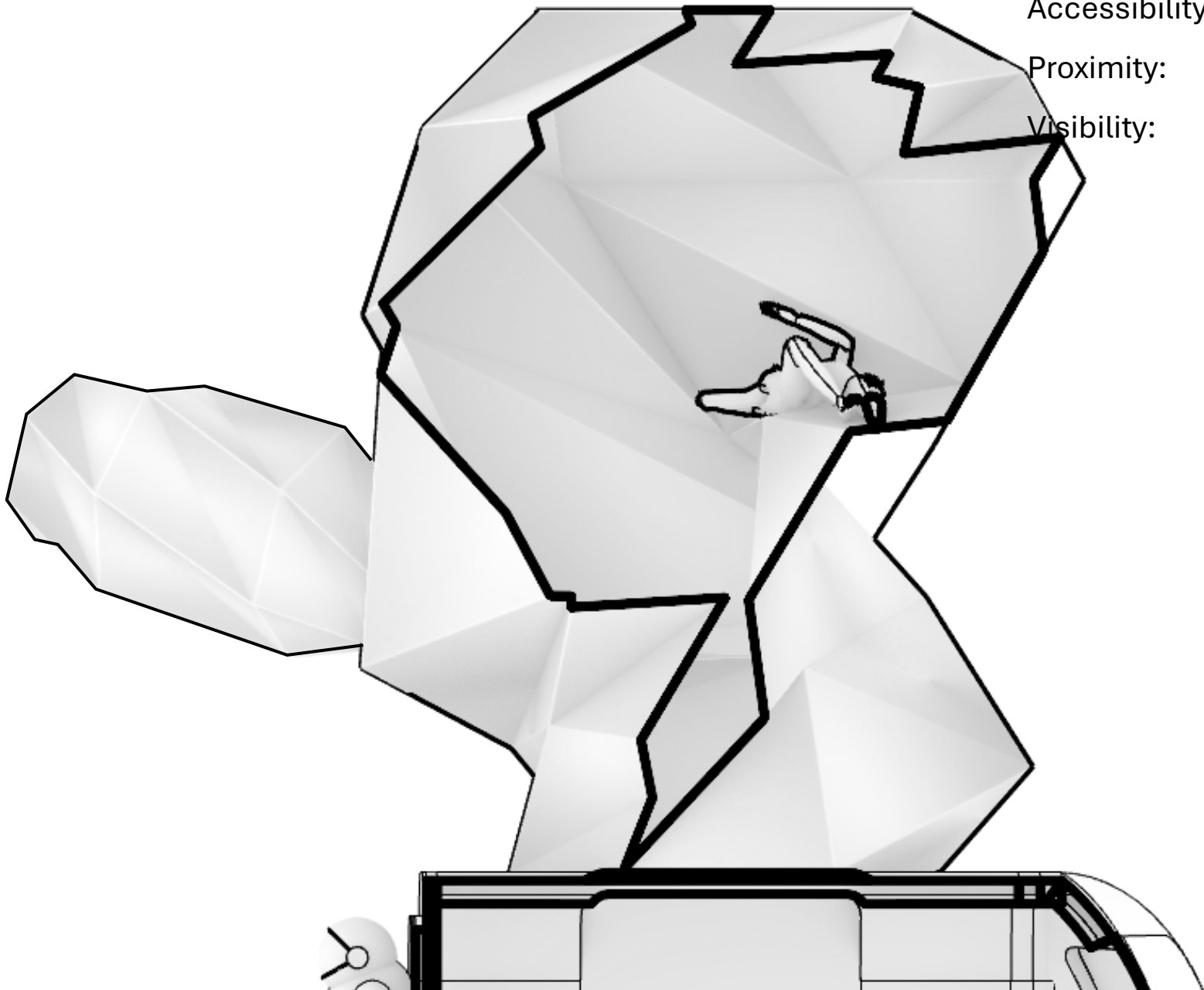
Accessibility:



Proximity:



Visibility:



Dining

Degree of social interaction: 5

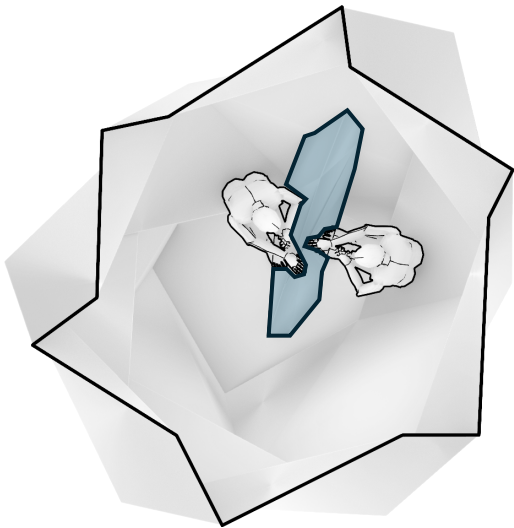
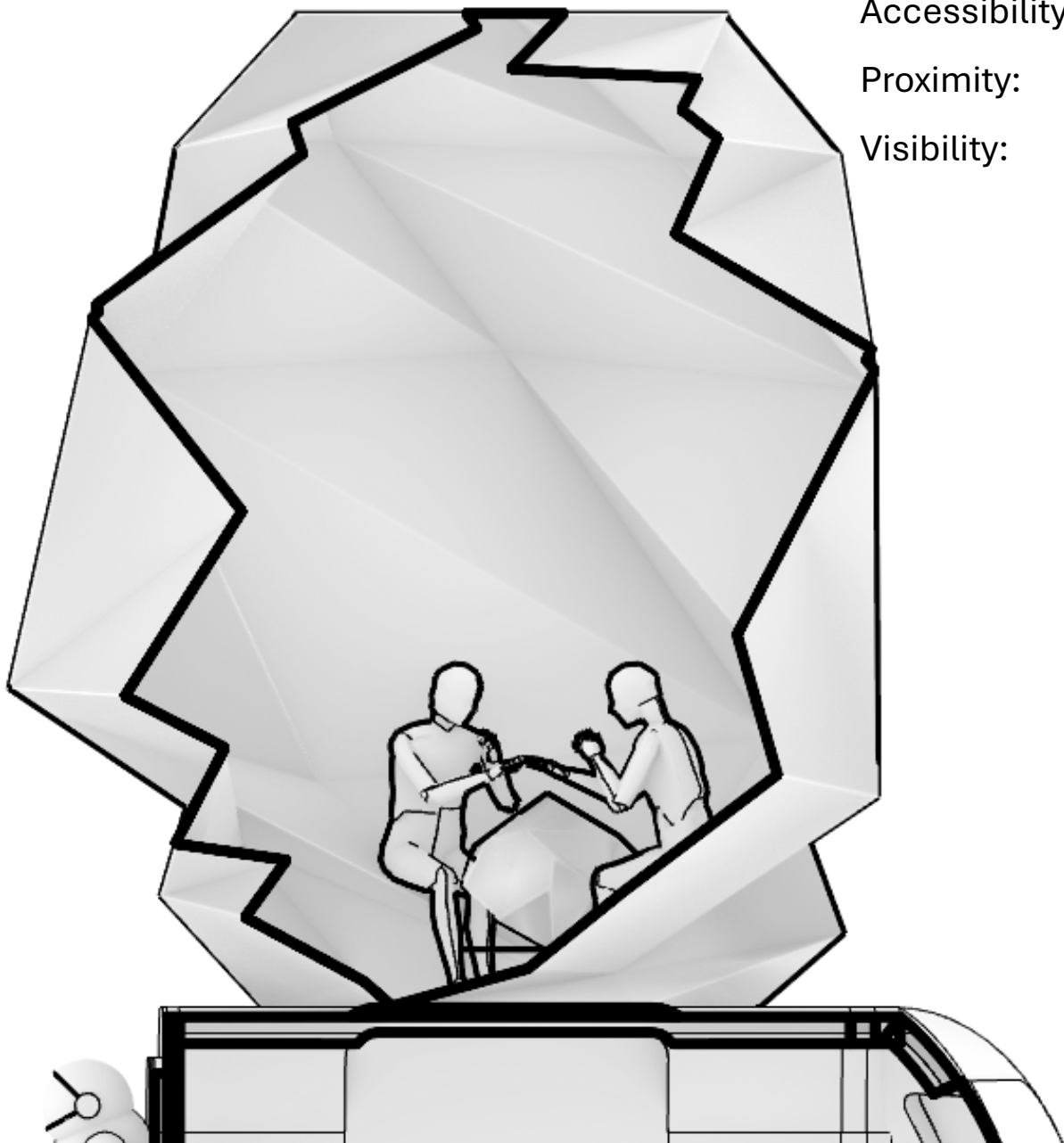
Accessibility:



Proximity:



Visibility:



Work

Degree of social interaction: 4

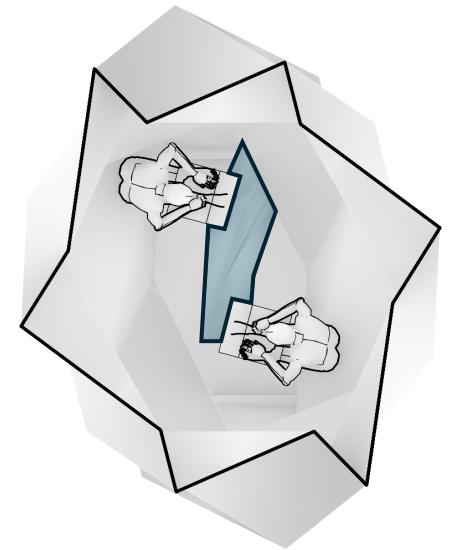
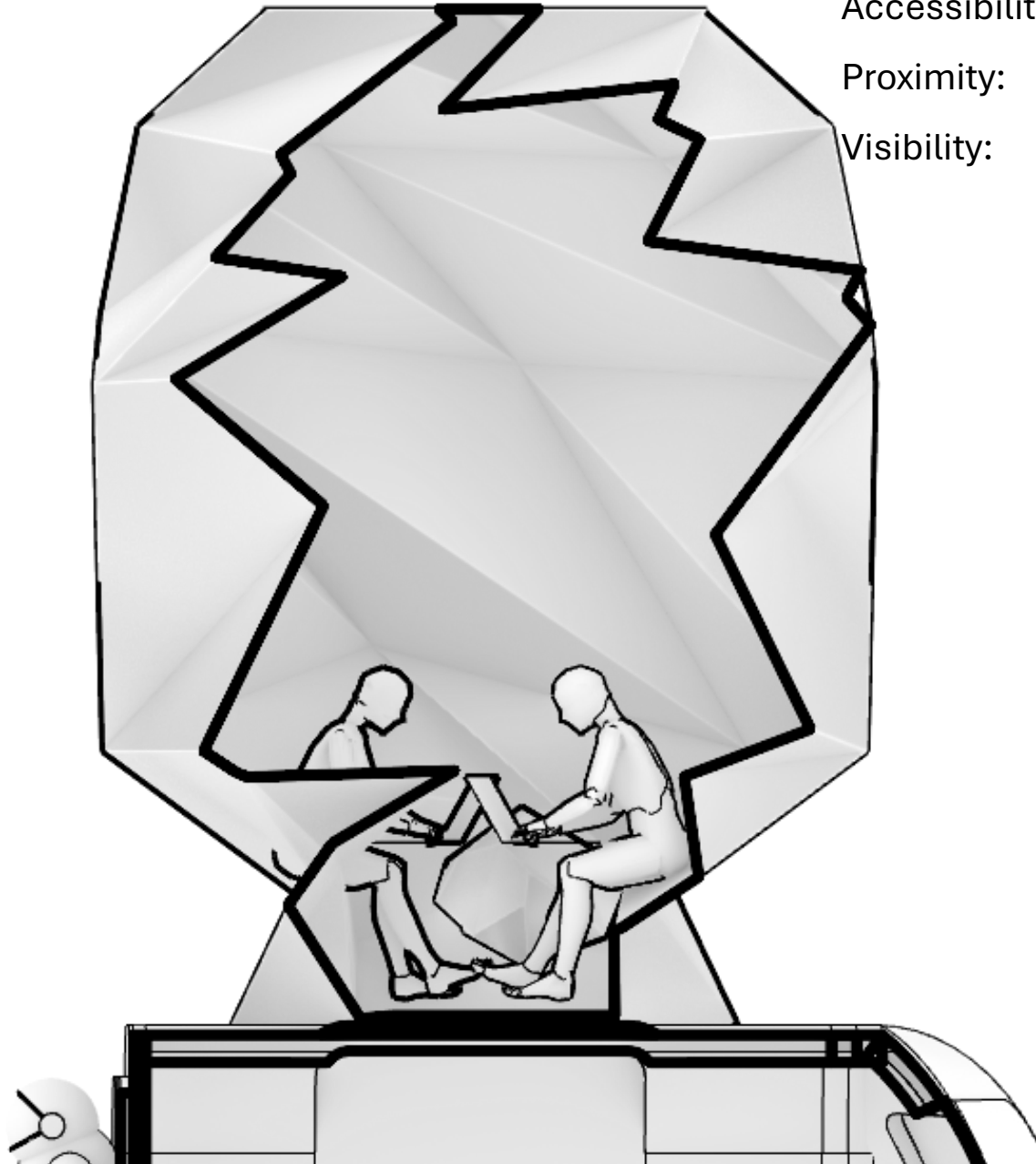
Accessibility:



Proximity:

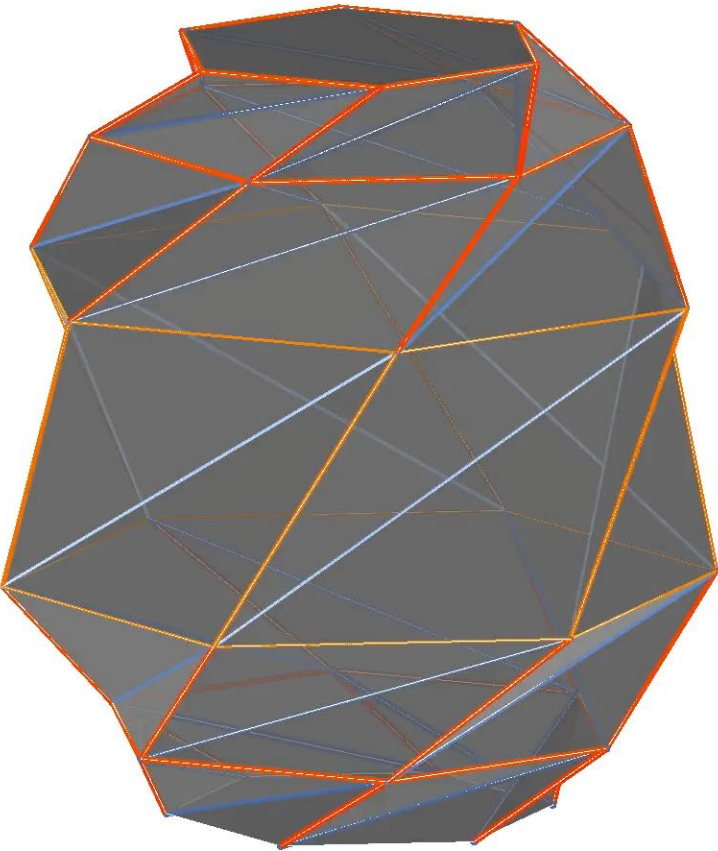


Visibility:

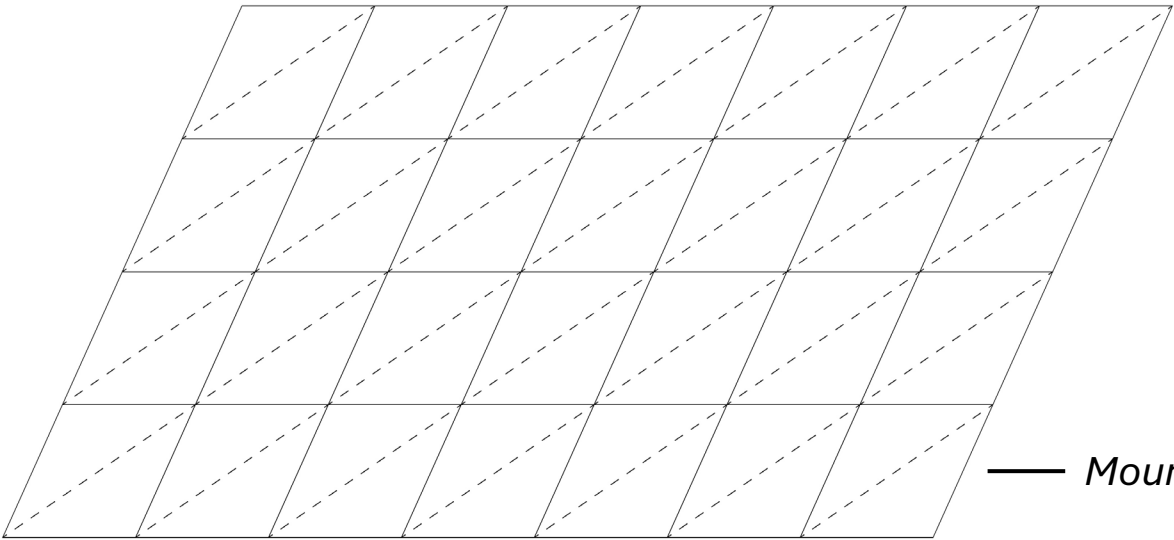


Structural optimization

Structural Analysis

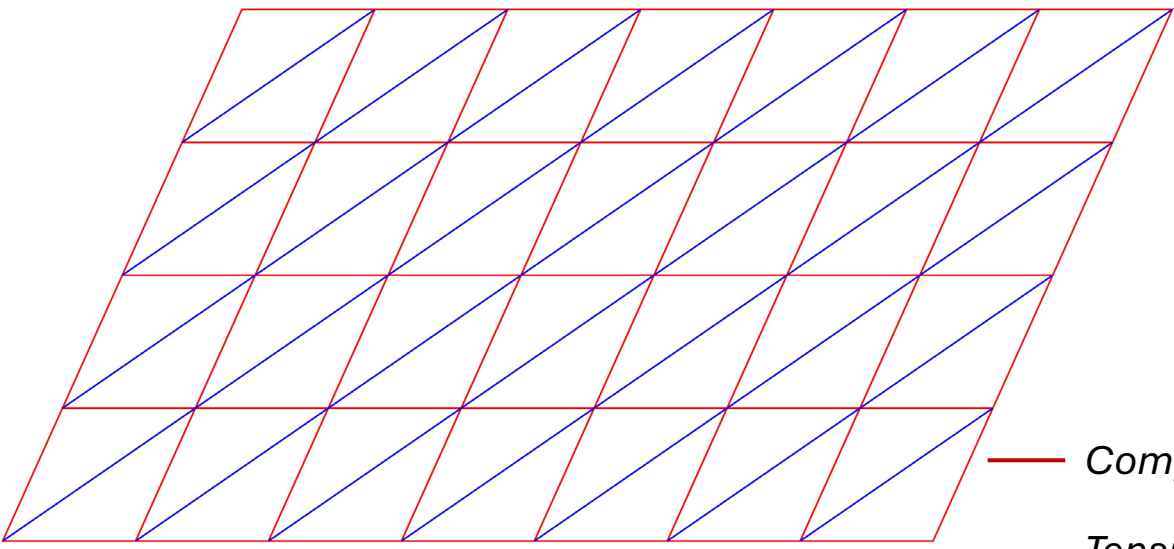


Default



— Mountain lines
- - - Valley lines

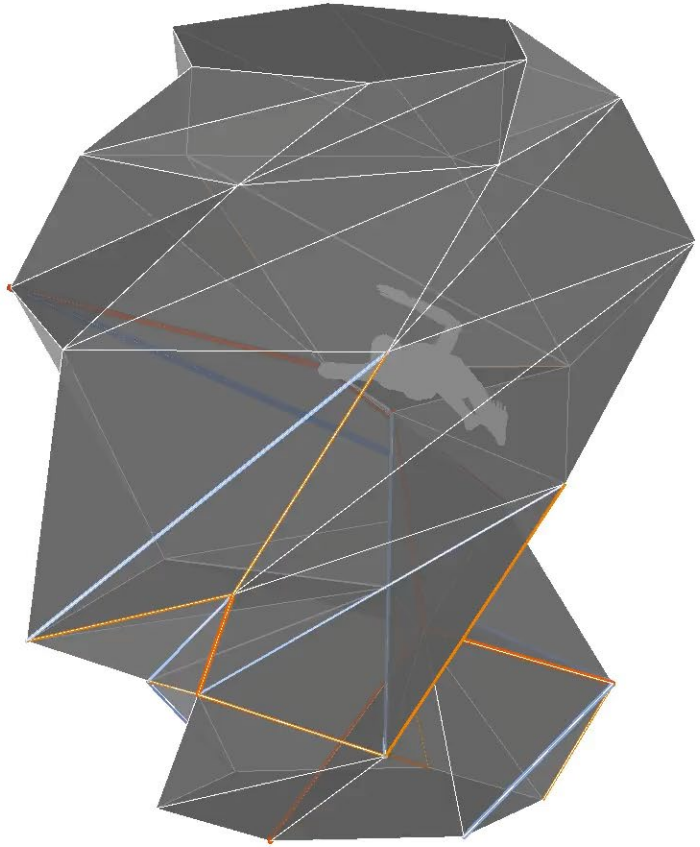
Mountain and valley creases



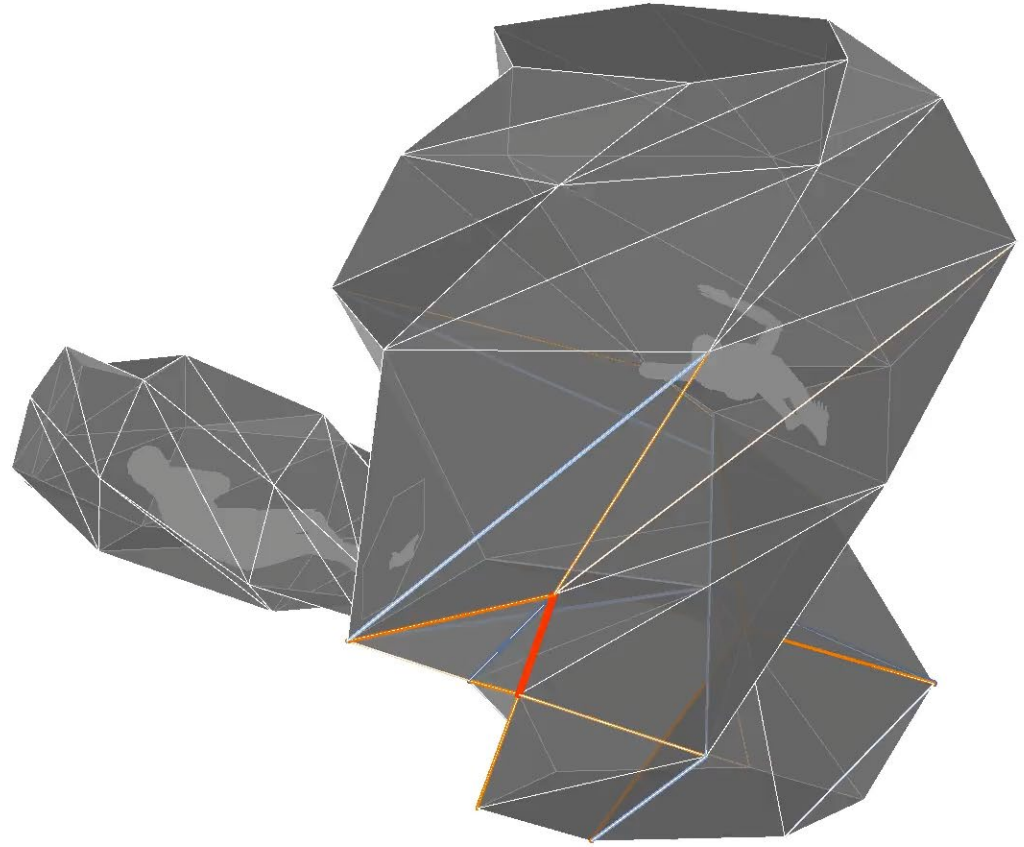
— Compression
— Tension

Compression and tension lines

Structural Analysis

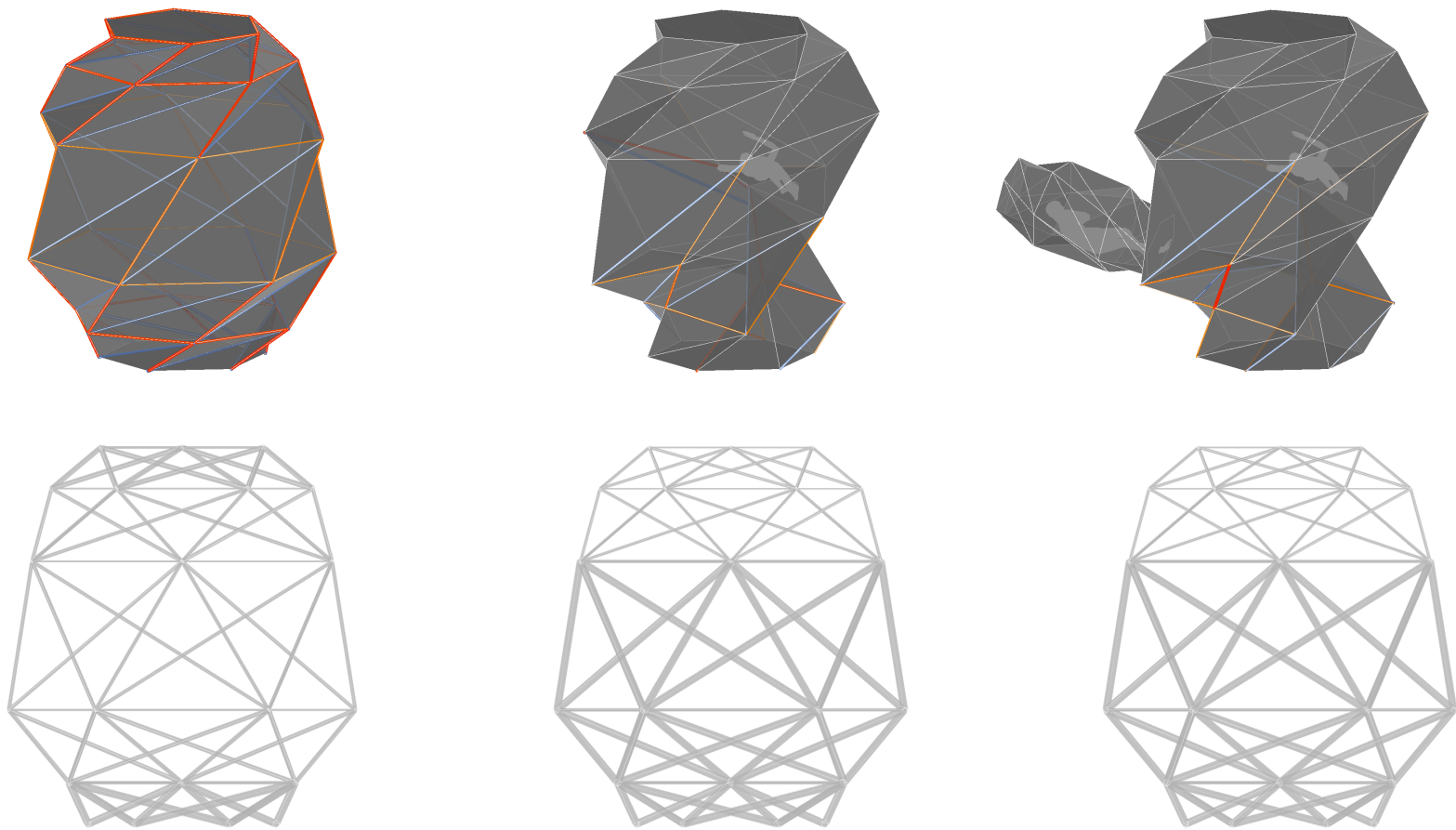


Leisure + work

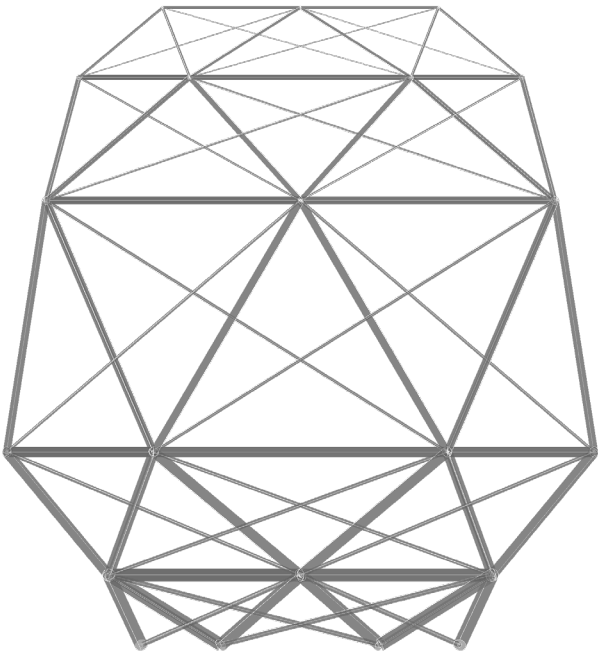


Both sleeping

Structural Analysis



*Thickness of pneumatic
muscles bladder material*



*Structural efficiency
optimization*

Lighting

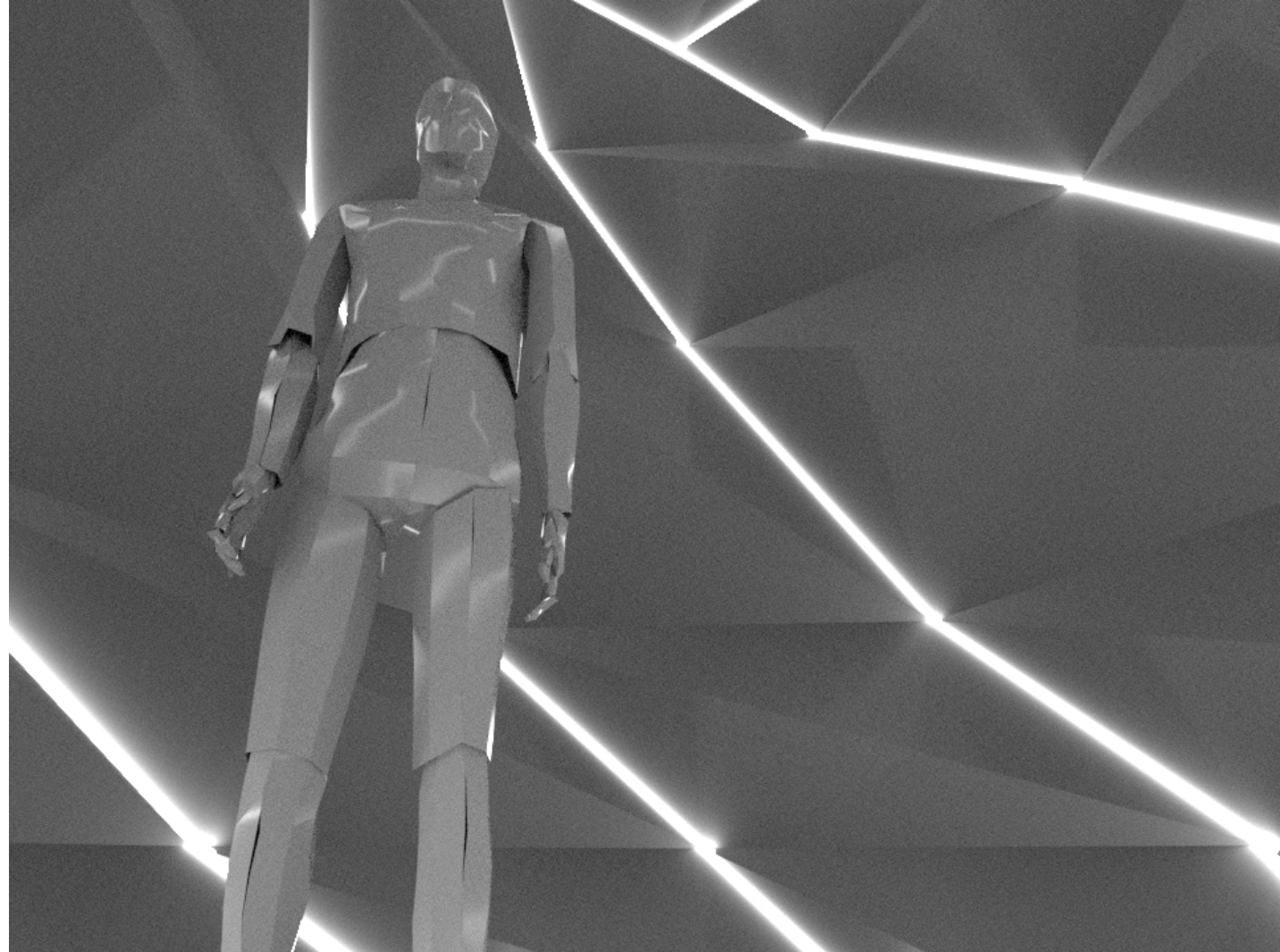
Lighting Design

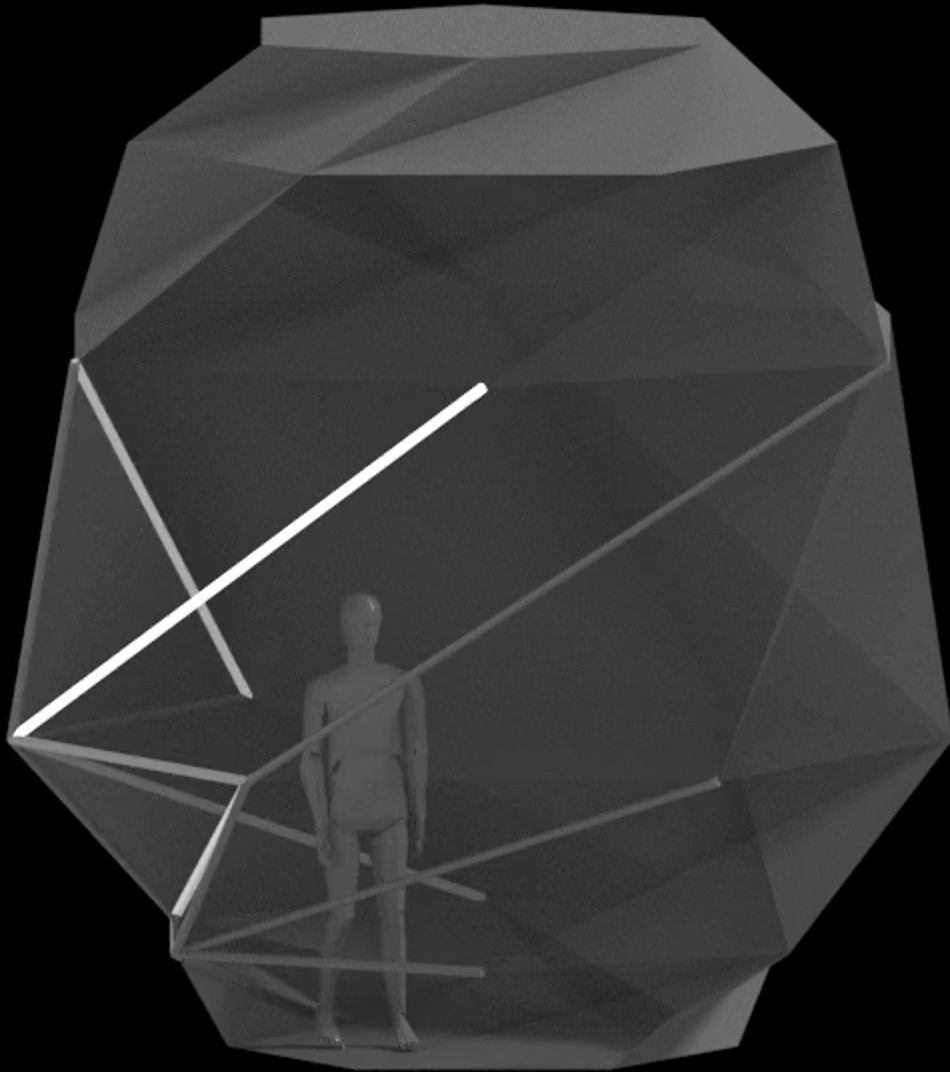
- *Lighting integrated with pneumatic muscles*
- *Concentrated brighter lighting*



Lighting Design

- *Lighting integrated with pneumatic muscles*
- *Evenly distributed uniform lighting*





Tracking lights

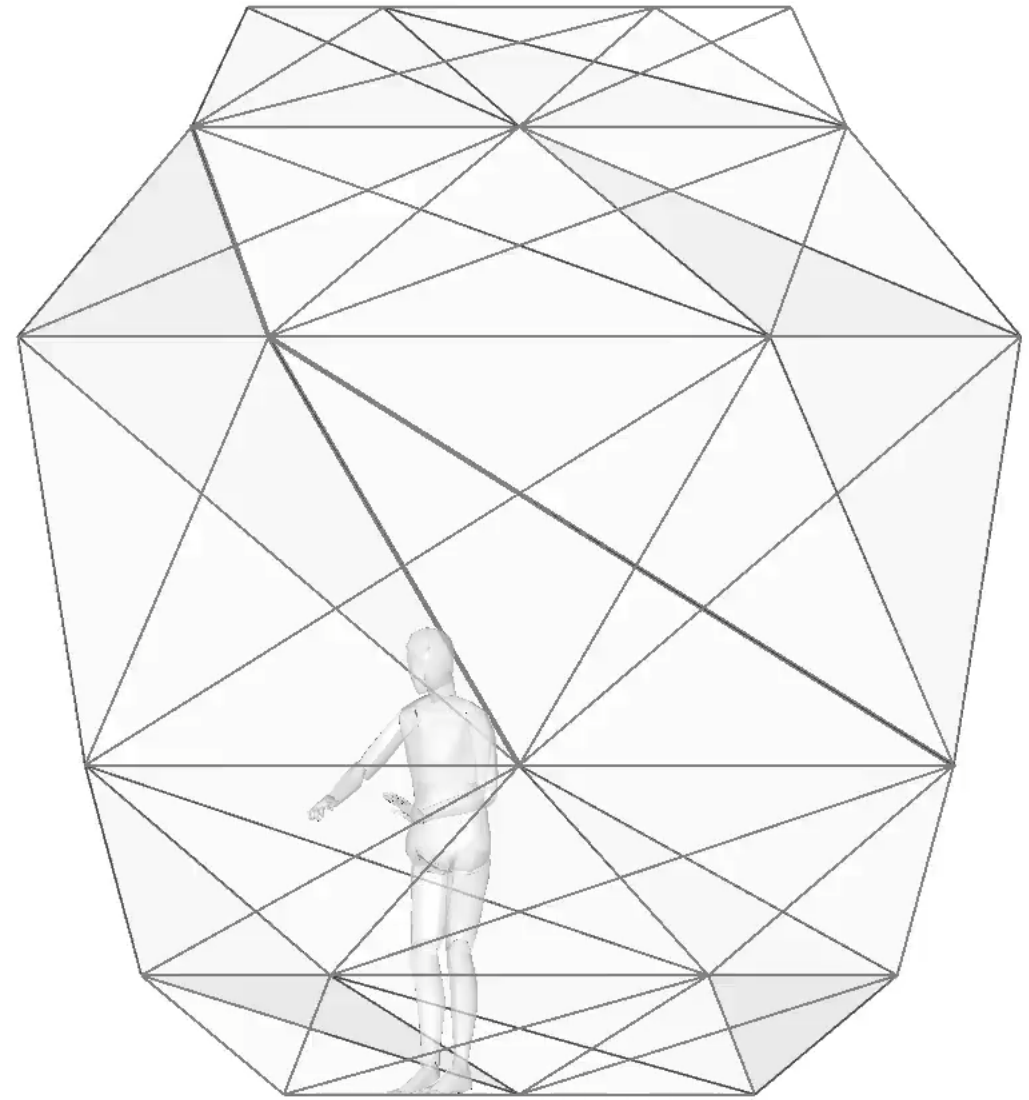
- *Brightness according to proximity sensor*
 - *Touch → activate*
 - *Closer → brighter*



Breathing lights

- *Brightness according to*
 - *activity recognition*
 - *music detection*

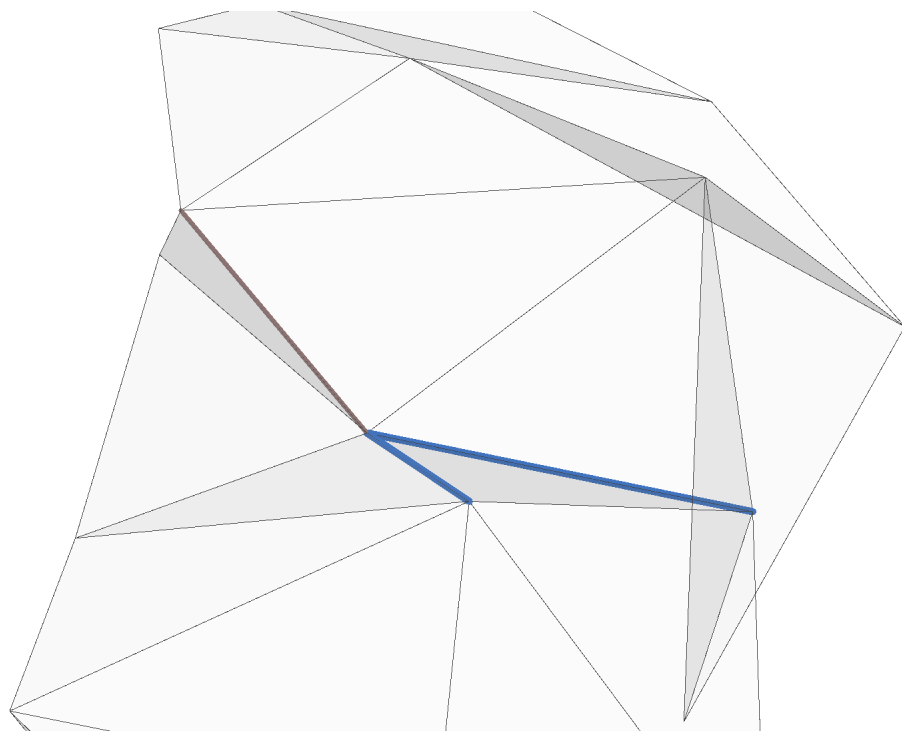
Physical Prototype



shorter

longer

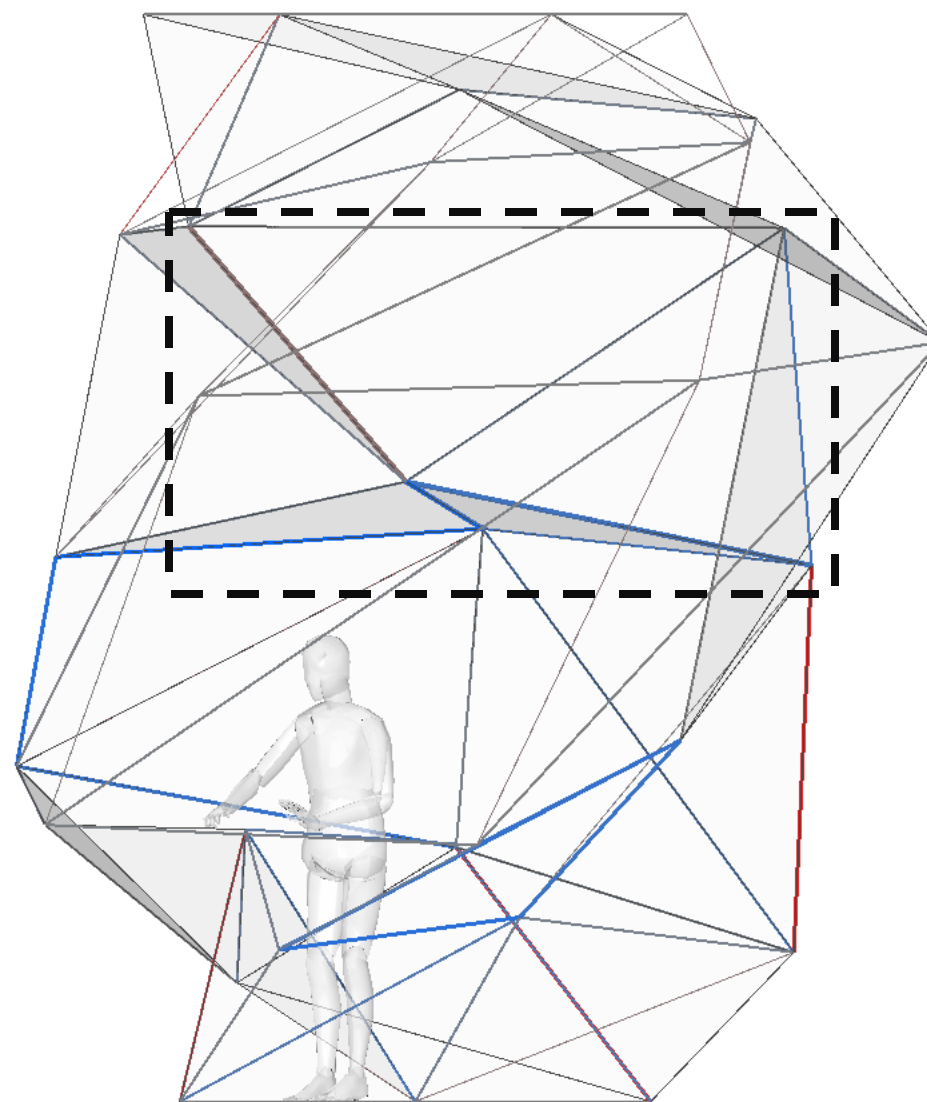
change in length in selected scenario



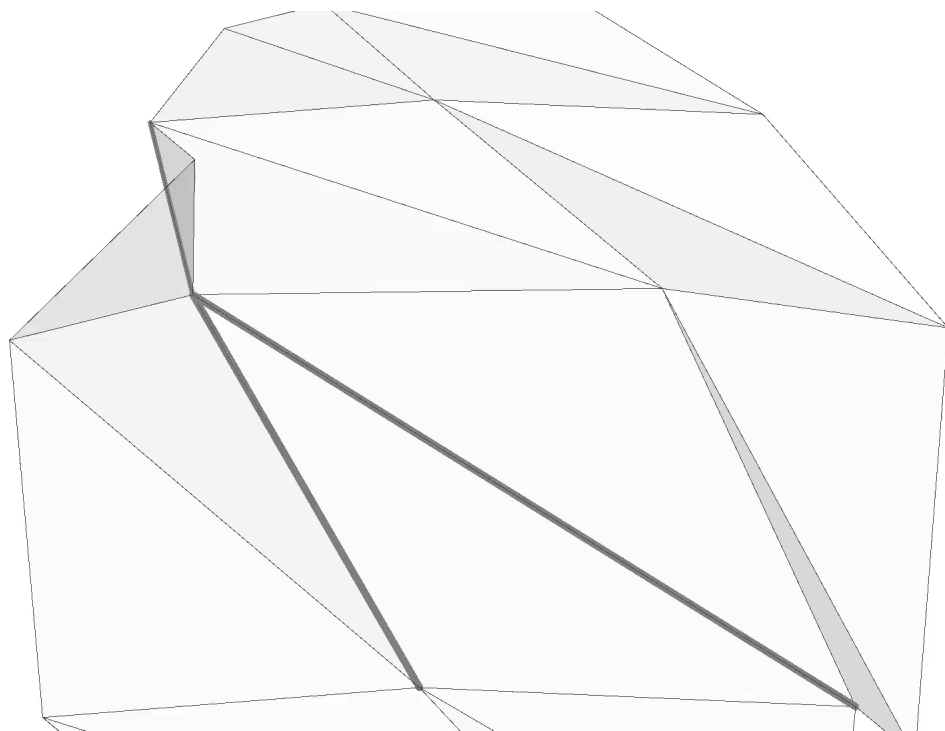
upper deck

shorter

longer



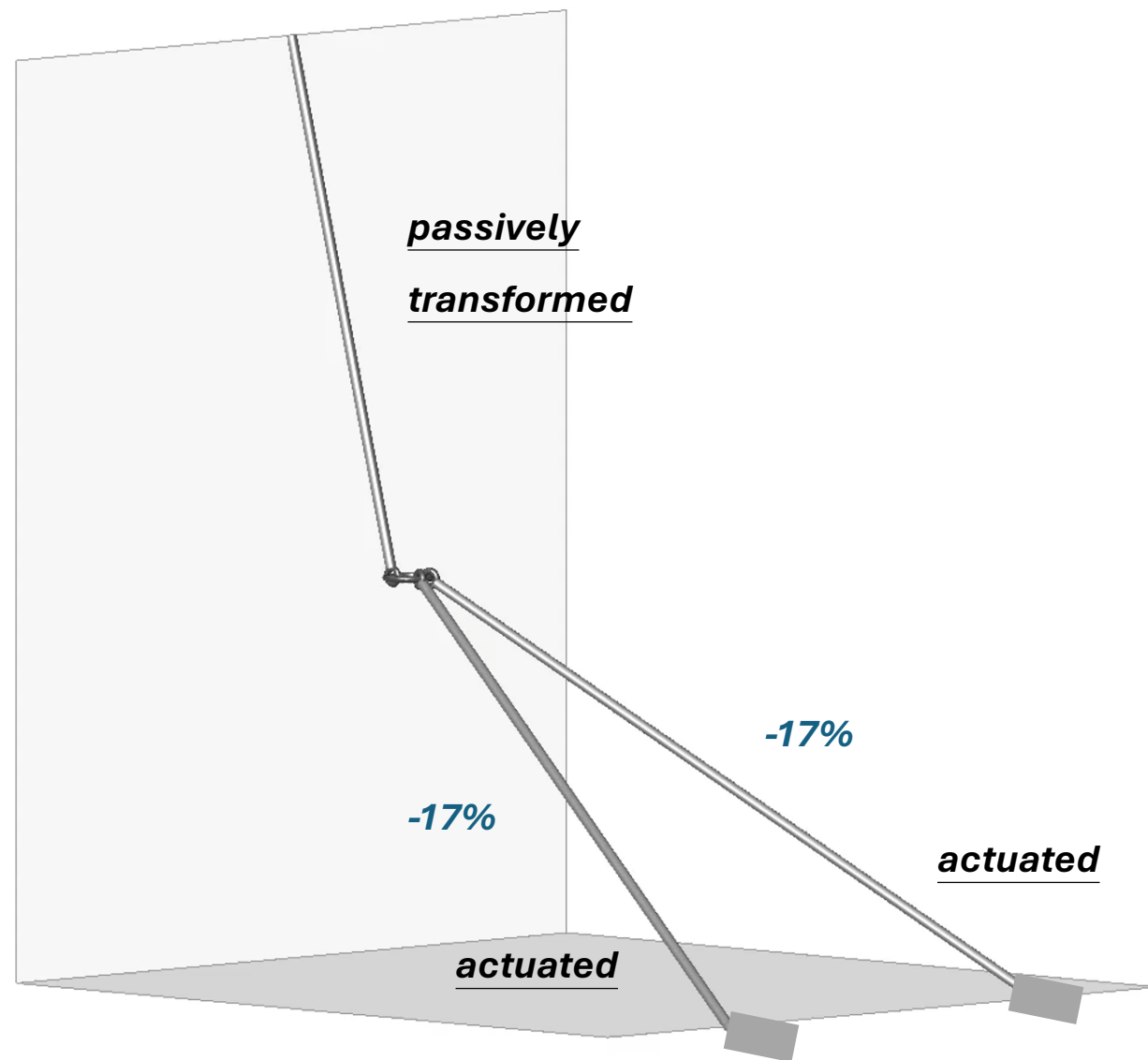
change in length in selected scenario



upper deck

shorter

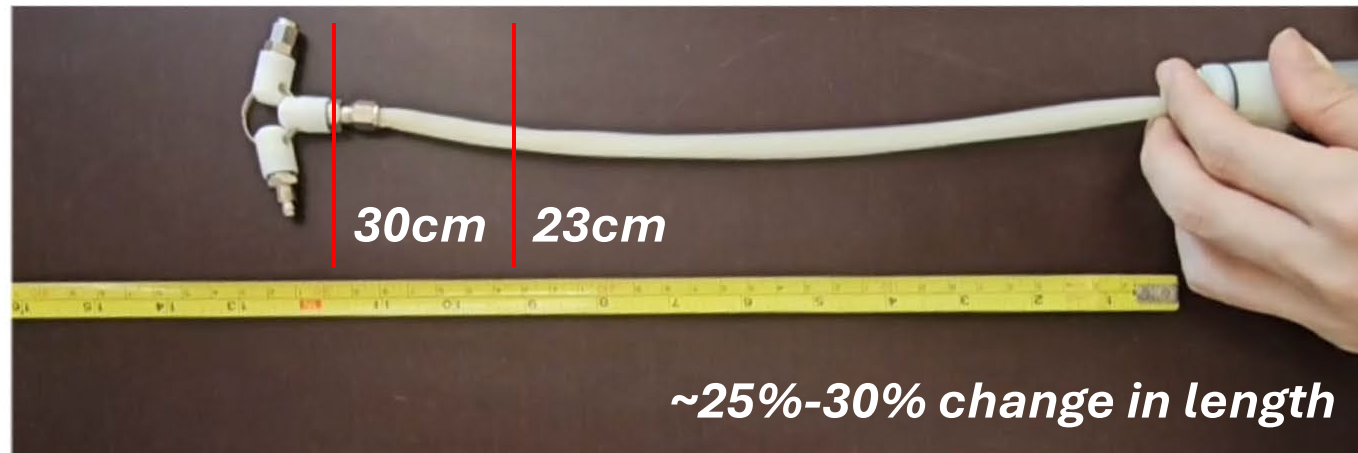
longer



selected prototype fragment



3mm thick silicone tube



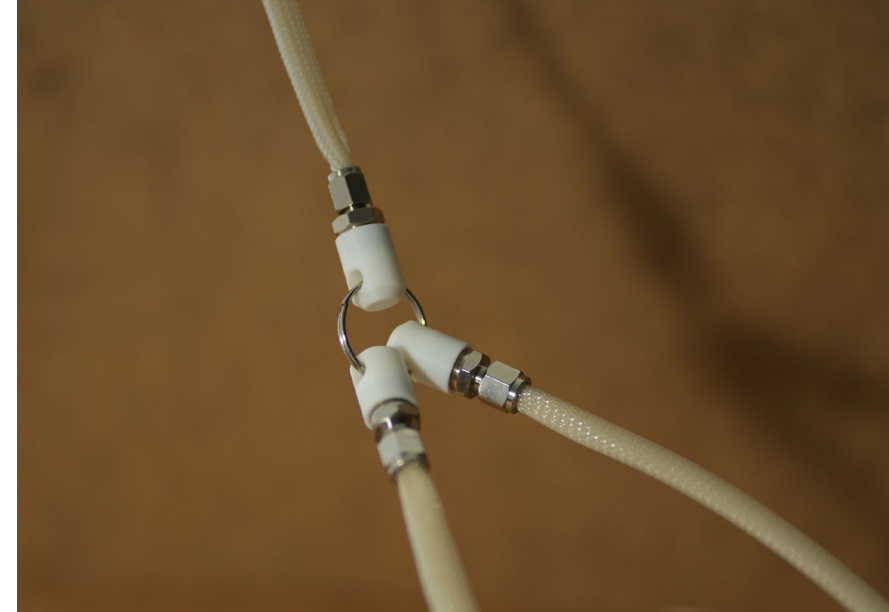
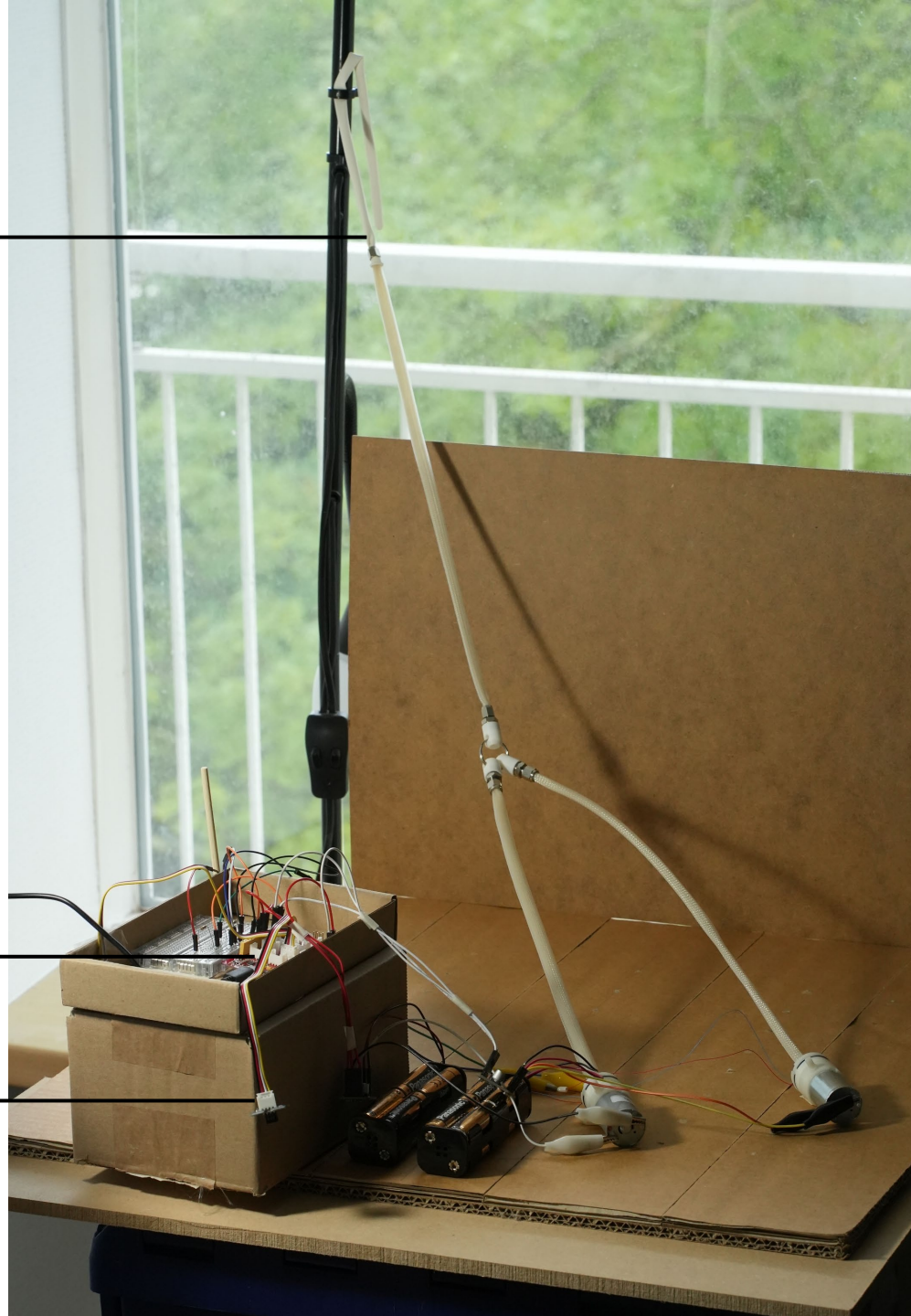
~25%-30% change in length

<0.5mm latex rubber tube

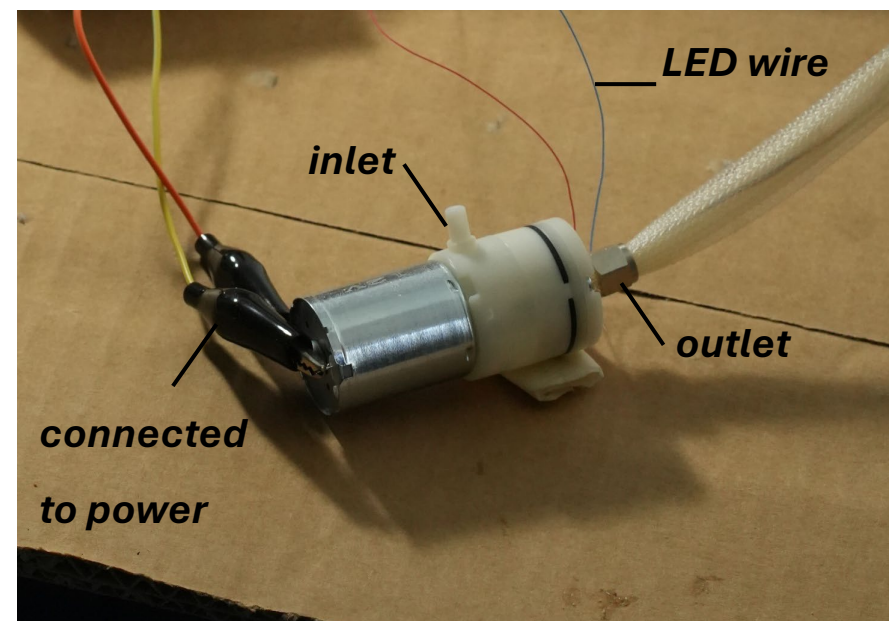
*free-end connected
to flexible rubber
material*

microcontroller

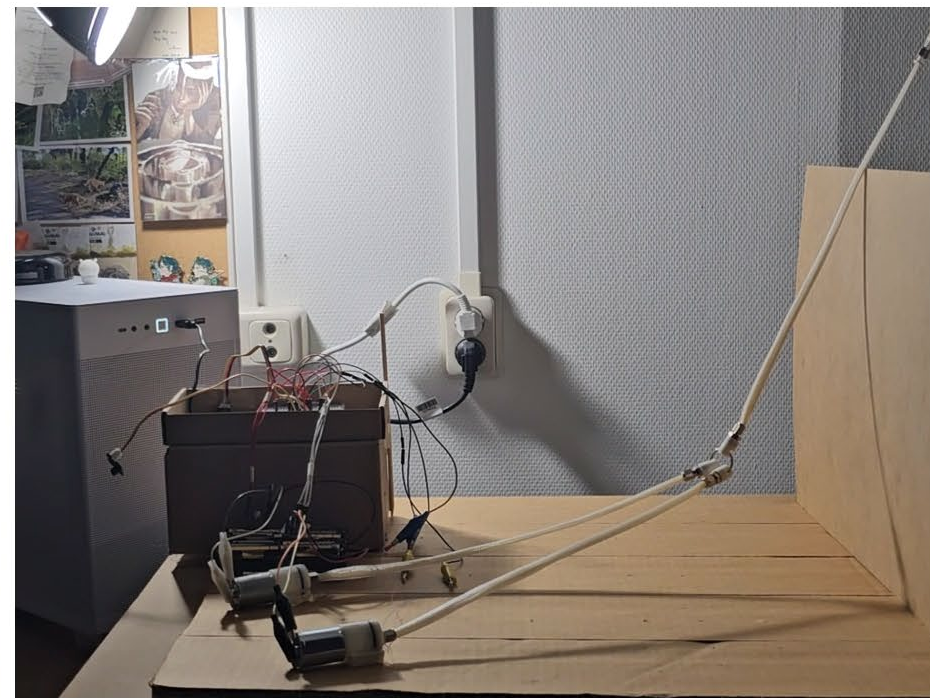
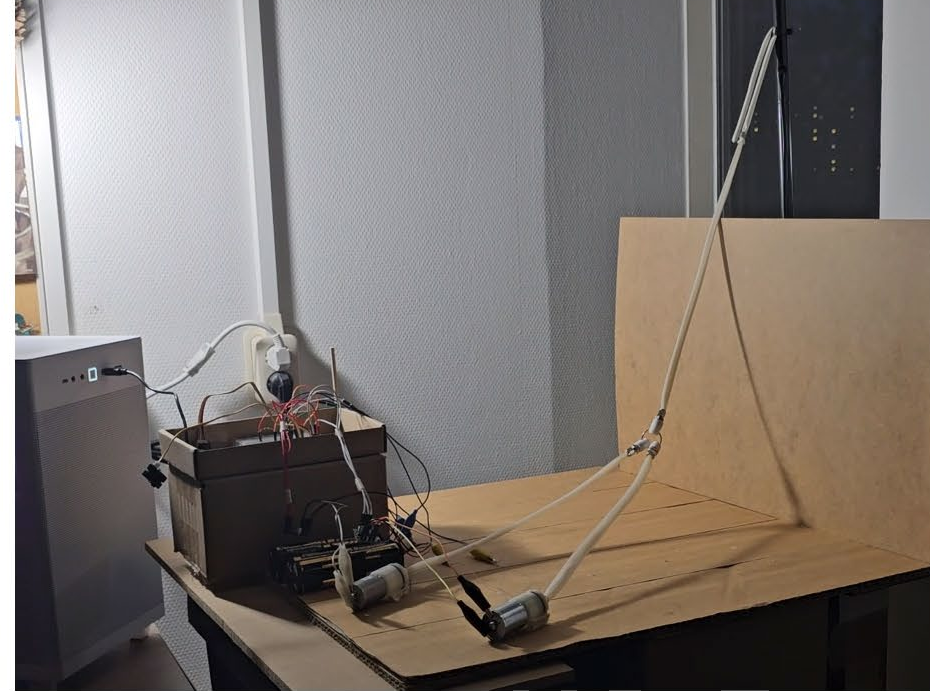
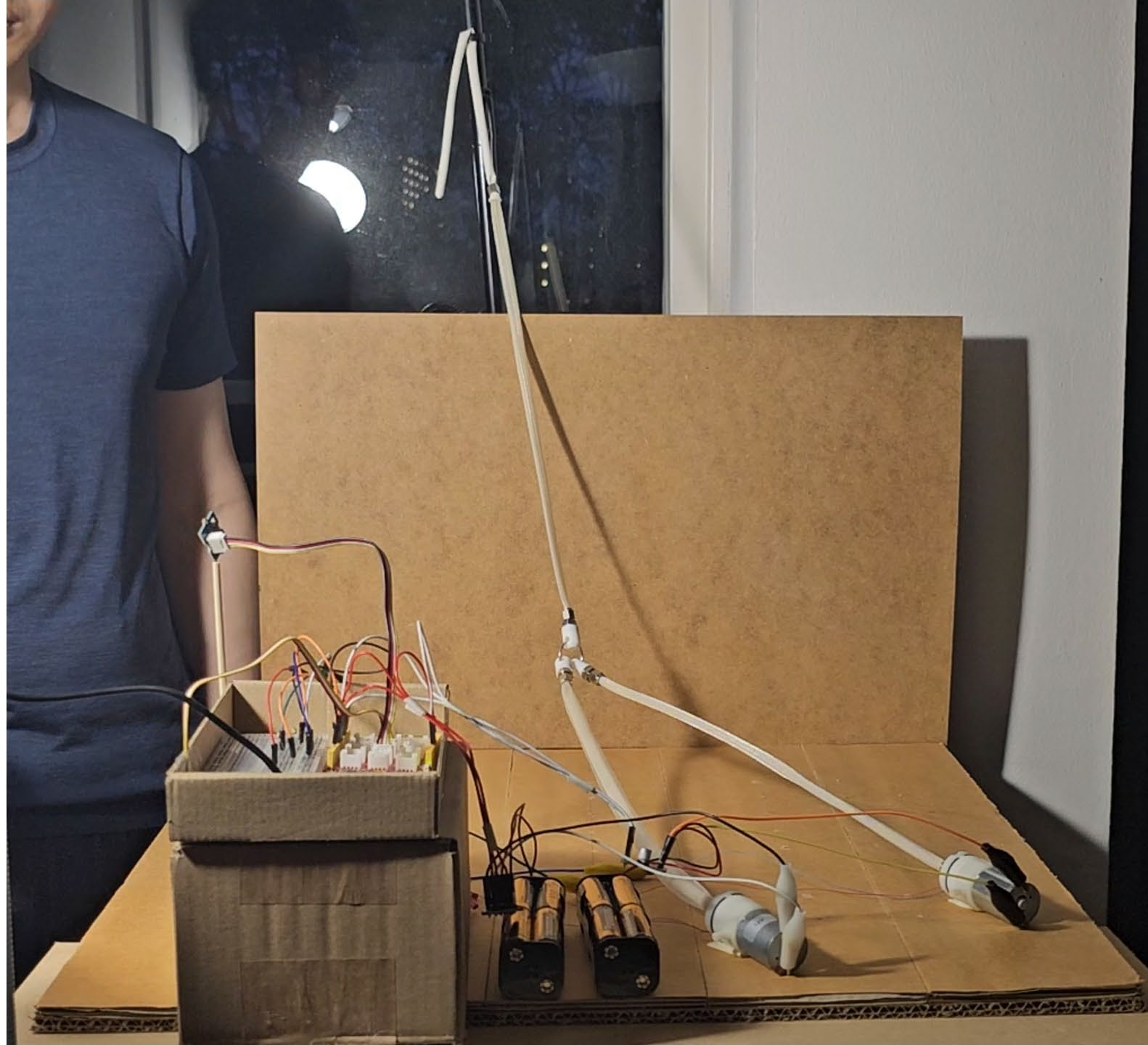
*infrared proximity
sensor*

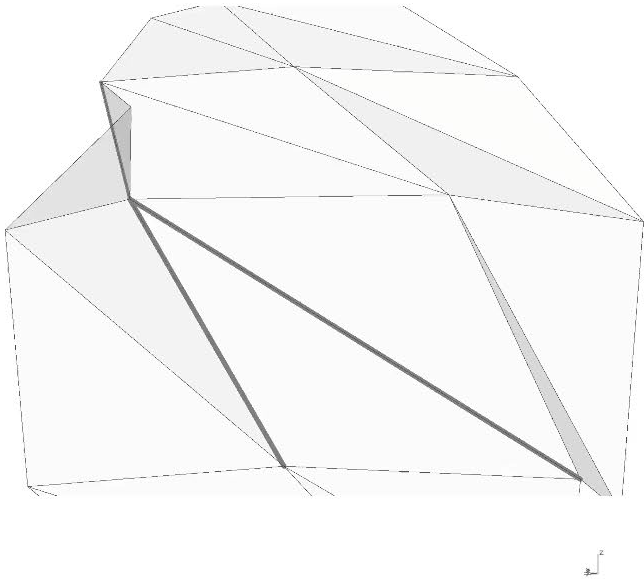


Ring joint for flexible orientation of muscles

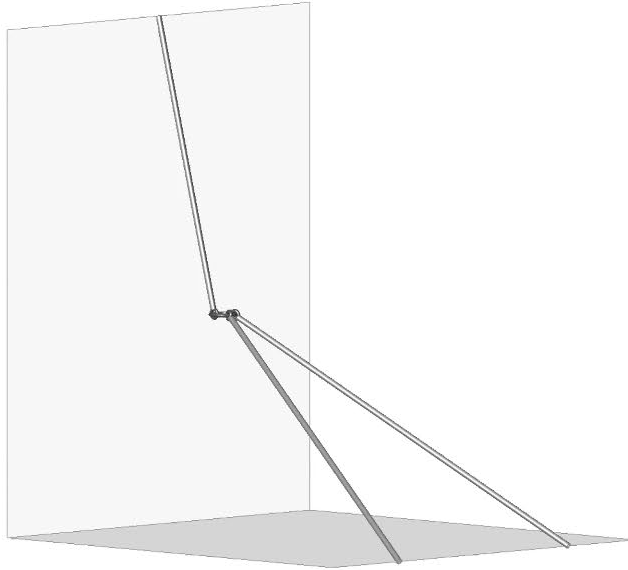


Close-up view

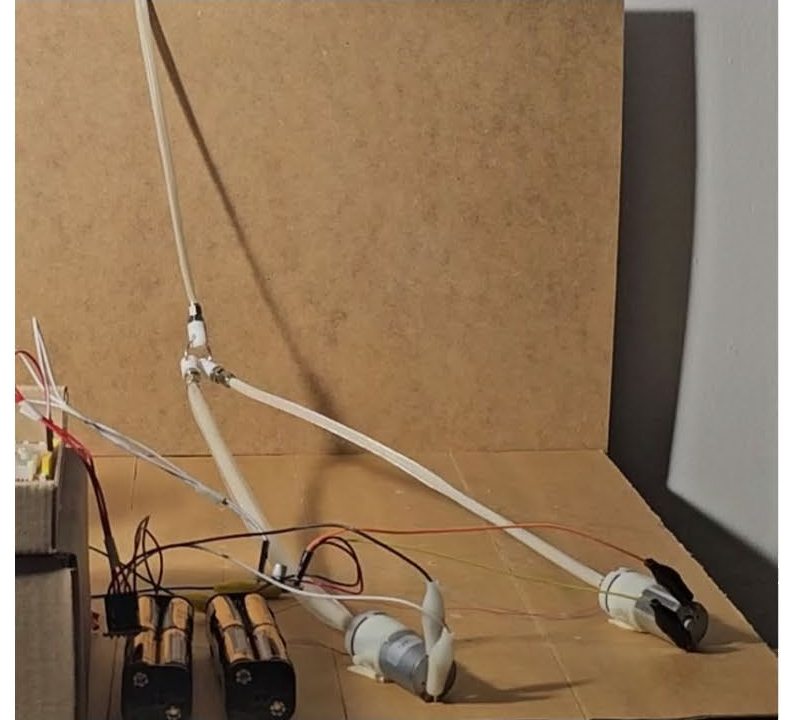




Design proposal



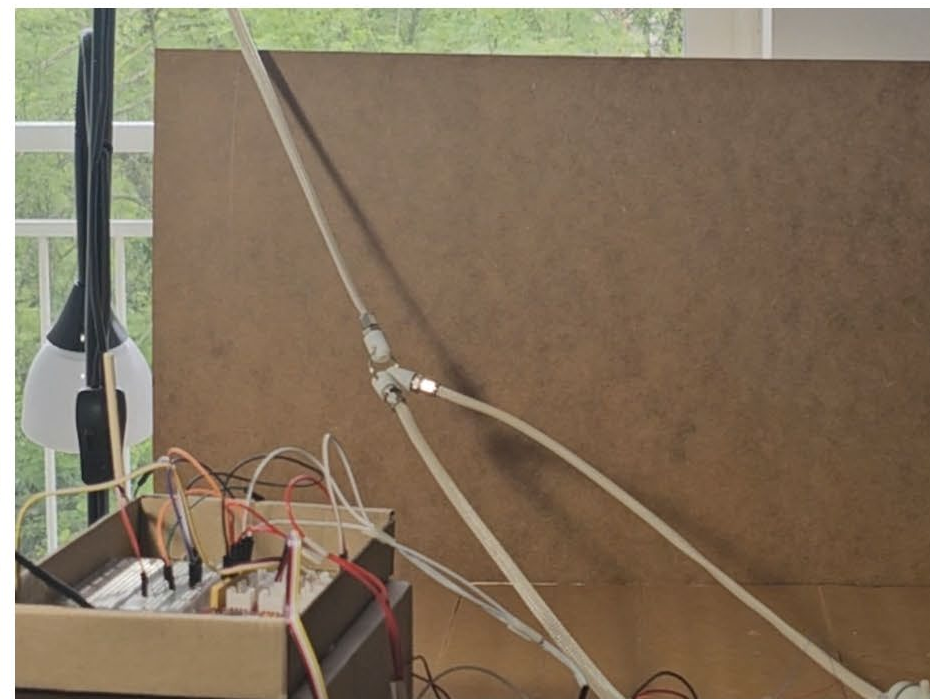
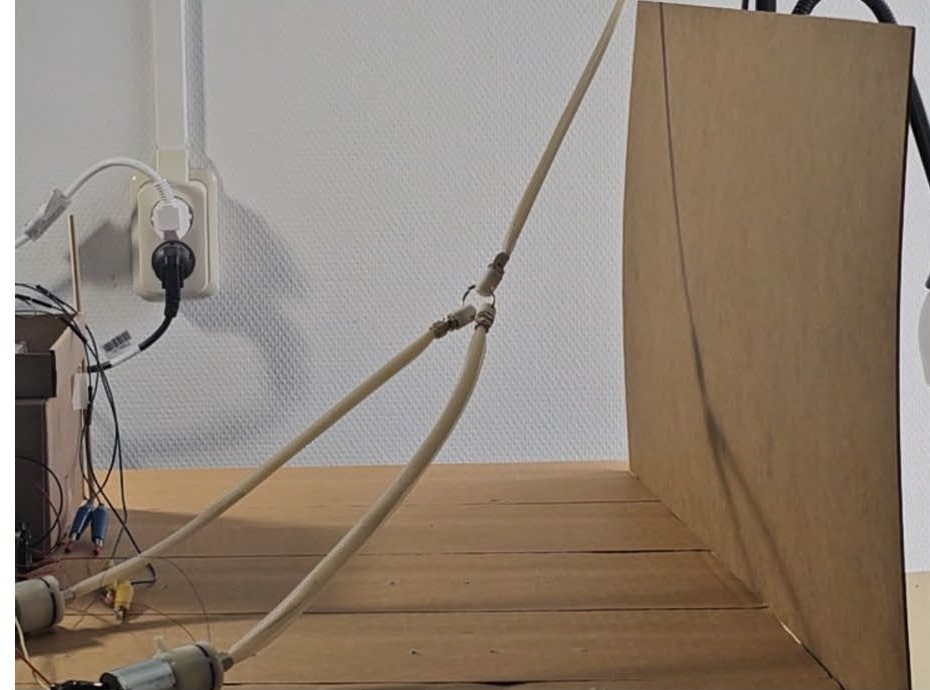
Simplified prototype
digital simulation



Simplified prototype
real life simulation



Alternating
muscle activation



Climate Control

Mobile Lunar Habitat

- Lack of natural ventilation
- Focus on **cooling**
- Dealing with metabolic heat from human body

Cooling

Heating from human body metabolism and machines

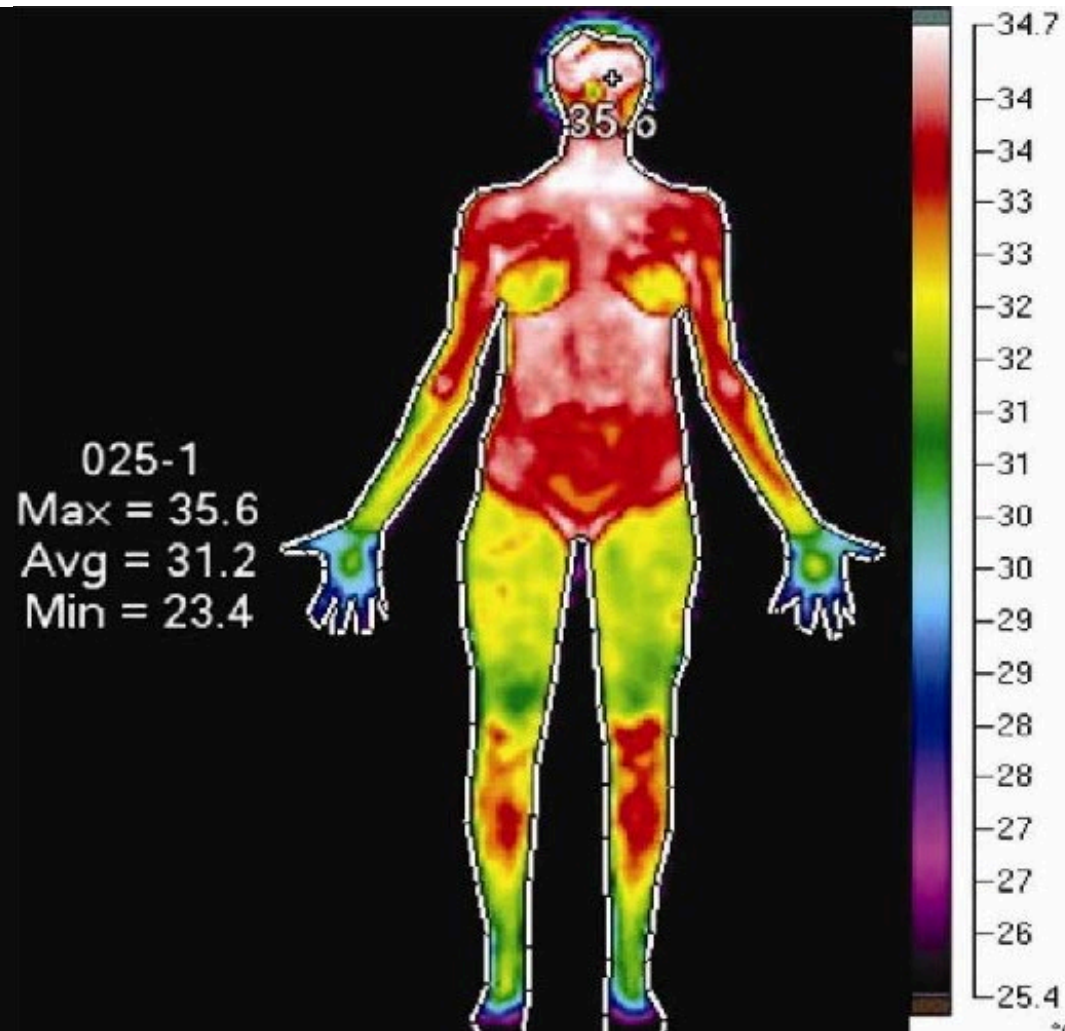
- **Continuous but smaller** extent of heat exchange
- **Heat recovery** instead of cooling
- Thermoelectric module (Peltier effect)
 - Convert heat into electricity
 - Sufficient for low-power sensors to operate
- Integrated to **wearables**

Heating

Sleeping/sickness/evaporation after sweating

- **Occasional but larger** extent of heat exchange
- Need for rest
 - In contact with surfaces for rest
 - Bench/bed
 - Packed in areas that is more associated with rest
- Integrated to **building system**

Cooling

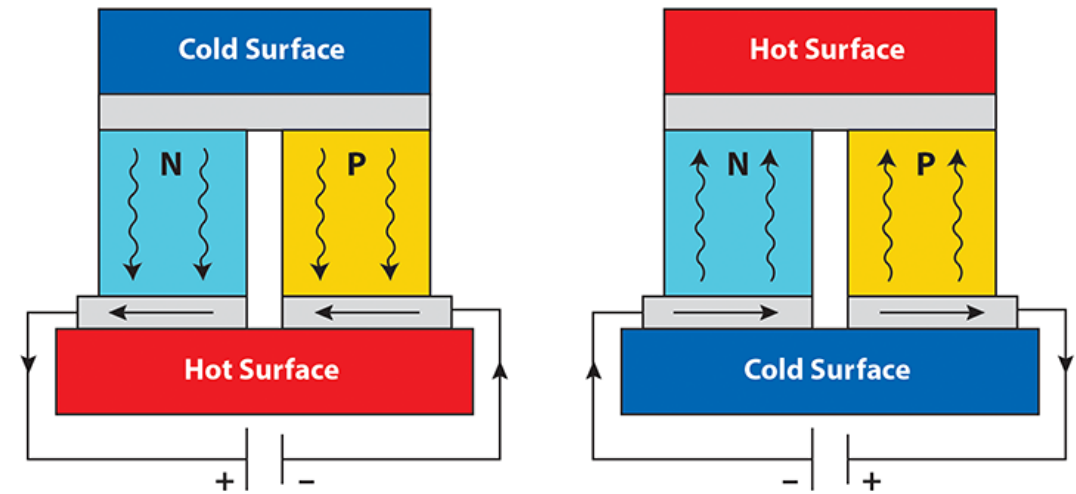
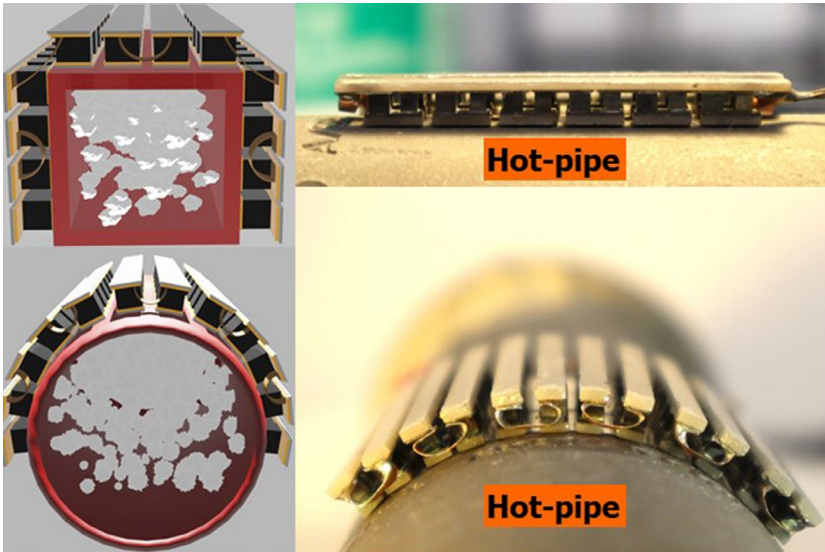
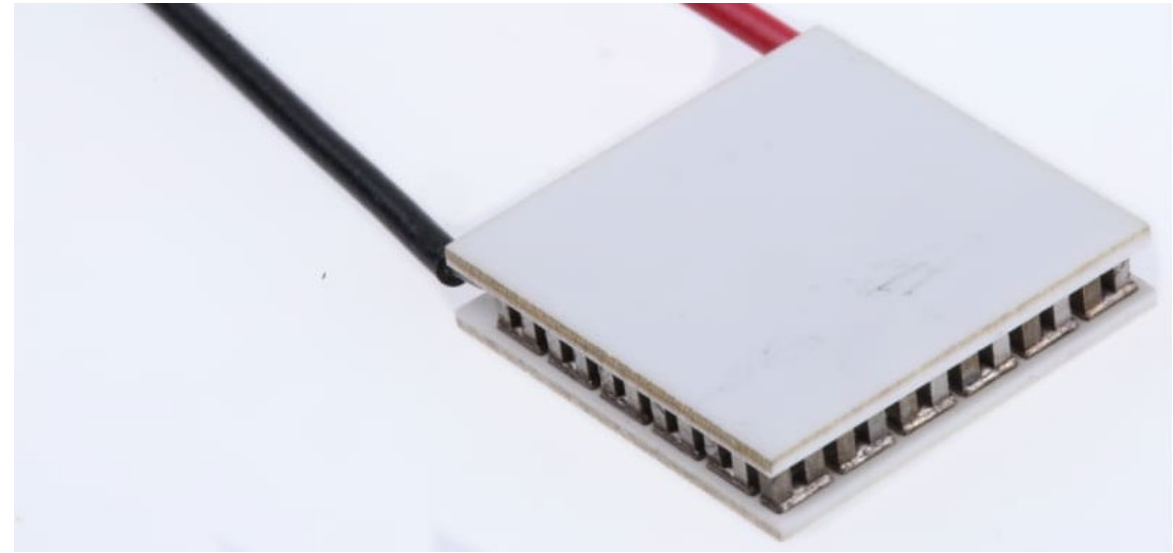


Cooling efficiency on human body

- The torso region (including the chest, abdomen, upper and lower backs) and head region (including the head, face and neck) have the largest amount of heat production and blood perfusion for a human body with a low metabolic rate

Thermoelectric module (Peltier Effect)

- Heating when supplied with electricity
 - Produce electricity when heated (in reverse)
 - Cooling effect
- Flexible thermoelectric module
 - Bendable

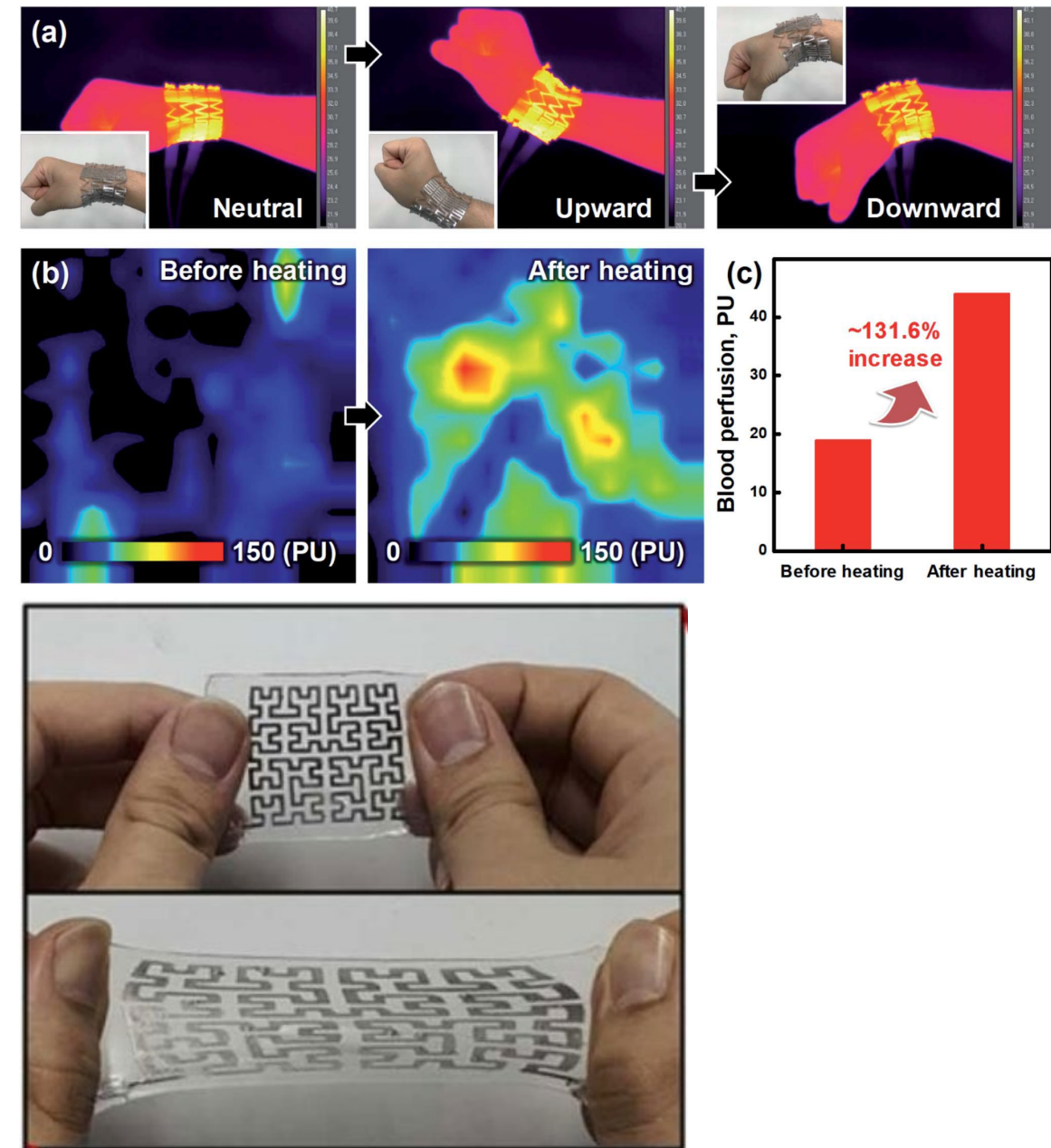


Thermoelectric heating and cooling and flexible module

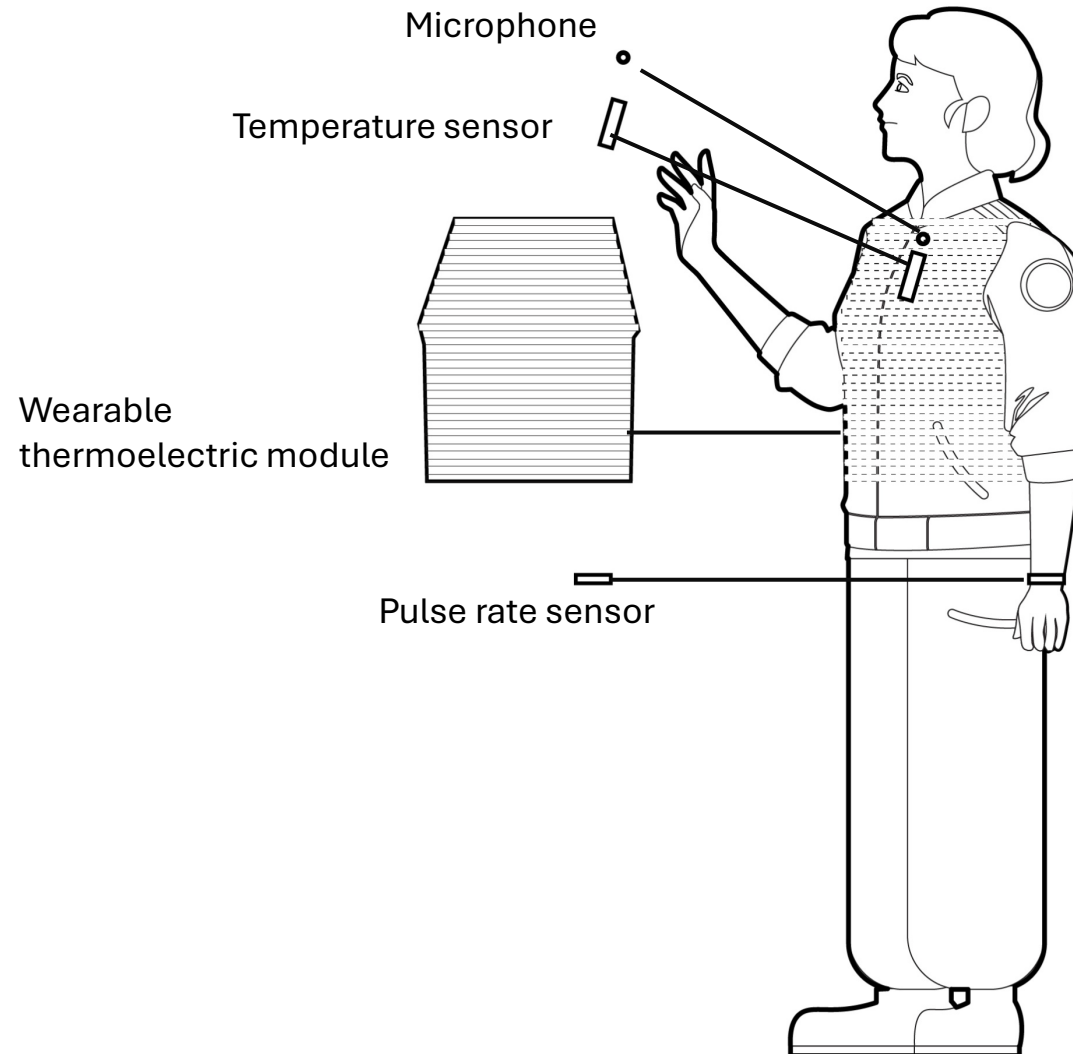
Heating – integrated to building envelope

Flexible heating element on envelope

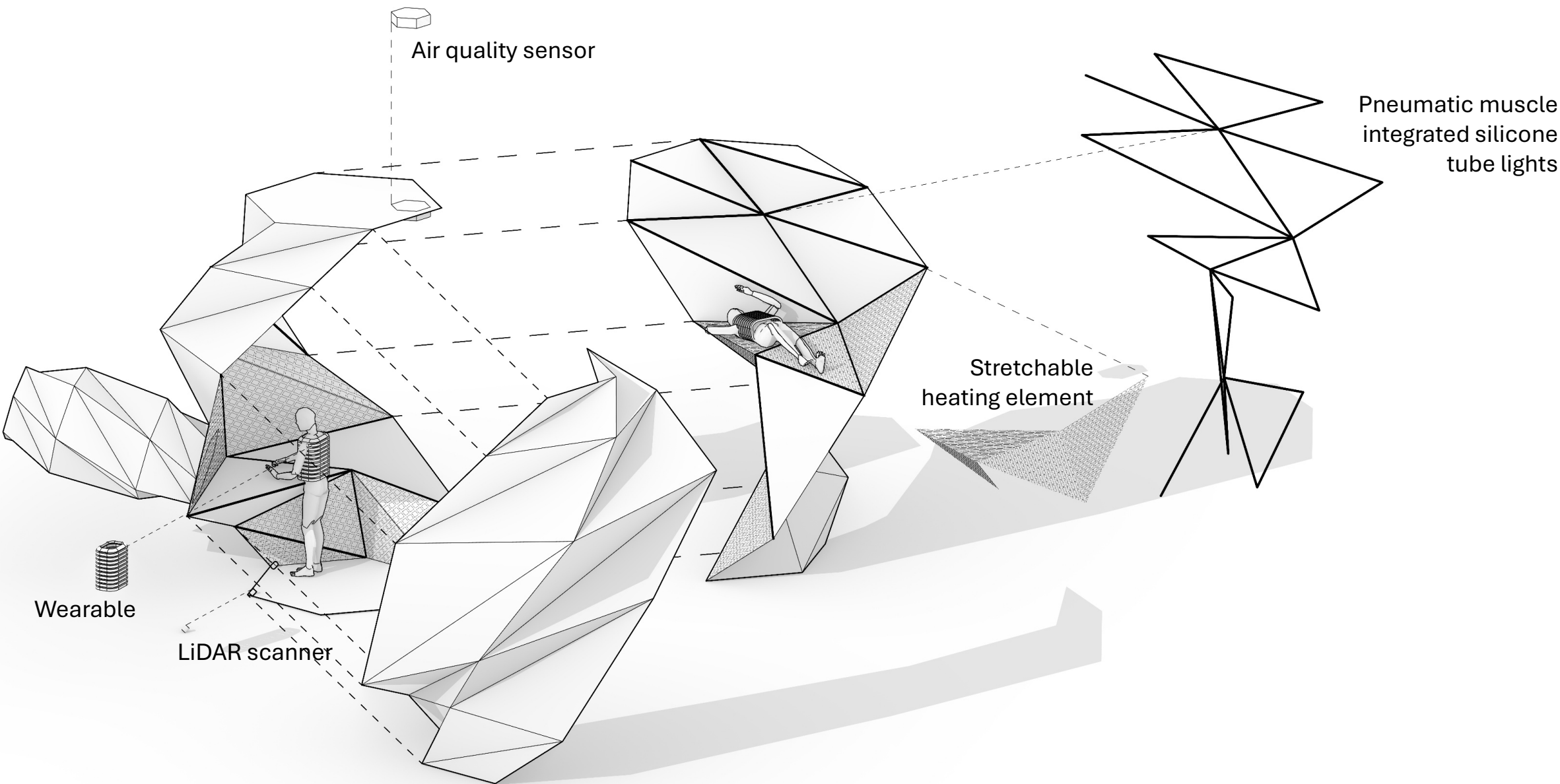
- Tibgrid® flexible heating fabric
 - Bendable
 - Stretchable
 - Heating elements fabricated in stretchable pattern



Cooling - Wearable



Sensor-actuator system overview



Envelope Material



Inflatable layers buildup (LIFE habitat by Sierra Space)

Internal barrier

- Protection from scratches

Redundant bladder

- Air containment with zero-permeability to air

Structural restraint

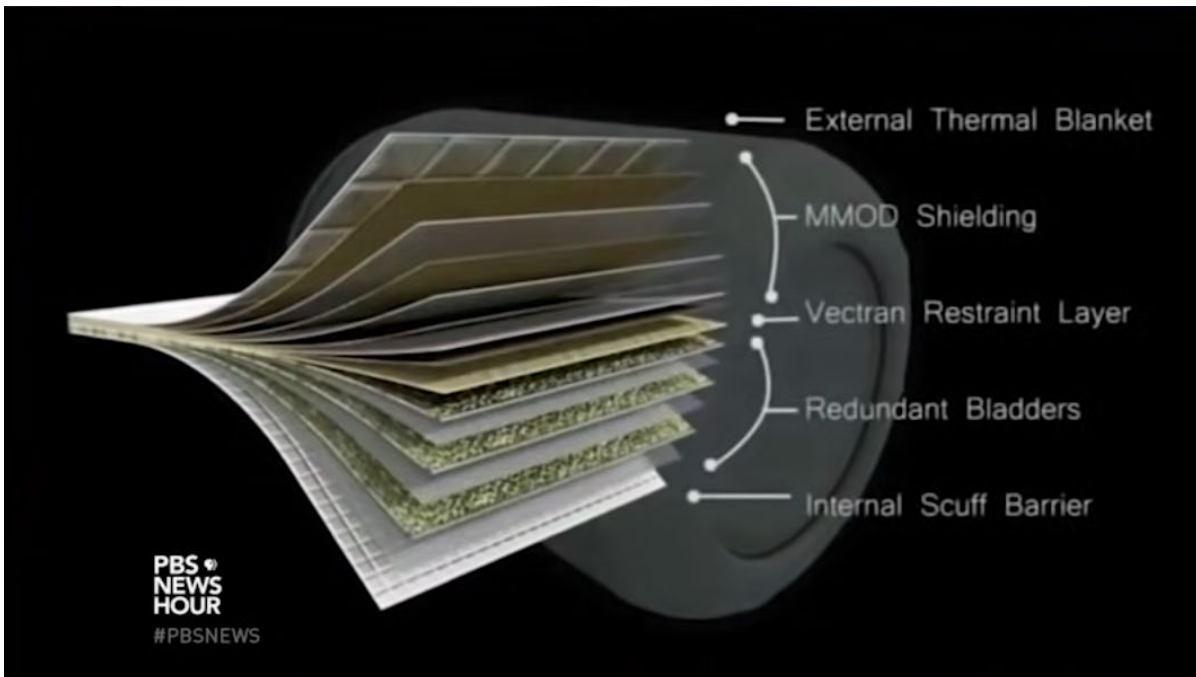
- Pressure load carrying capability to the inflatable structure
- Embedded with strain sensors for membrane damage detection and electric wires for energy supply
- Vectran™ fabric weave stronger than steel when inflated

MMOD shield

- Protection from Micro-Meteoroids & Orbital Debris impact

Multi-layer insulation

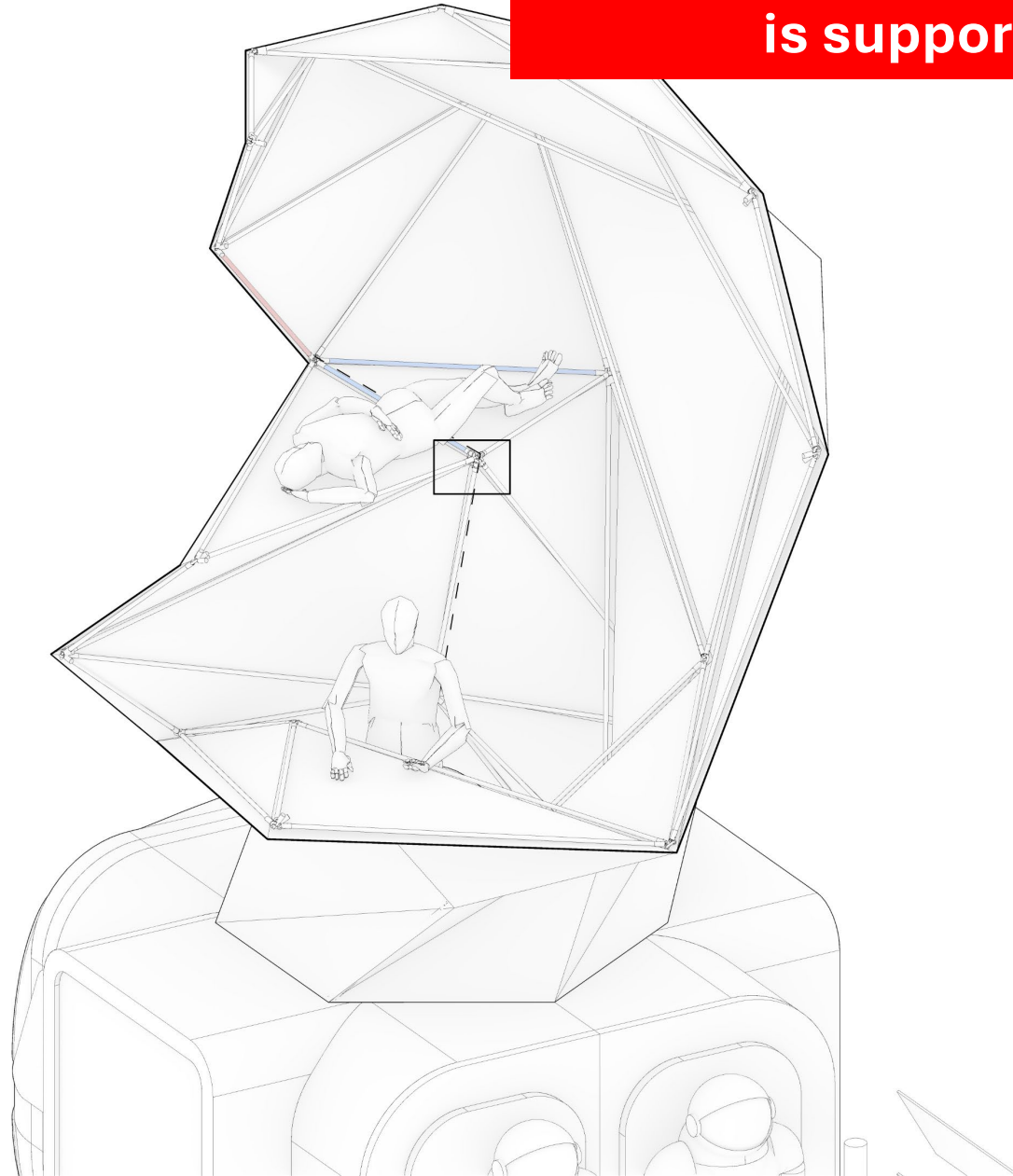
- Adequate thermal insulation from outer space environment
- Protection from atomic oxygen erosion and UV degradation



section

TBU

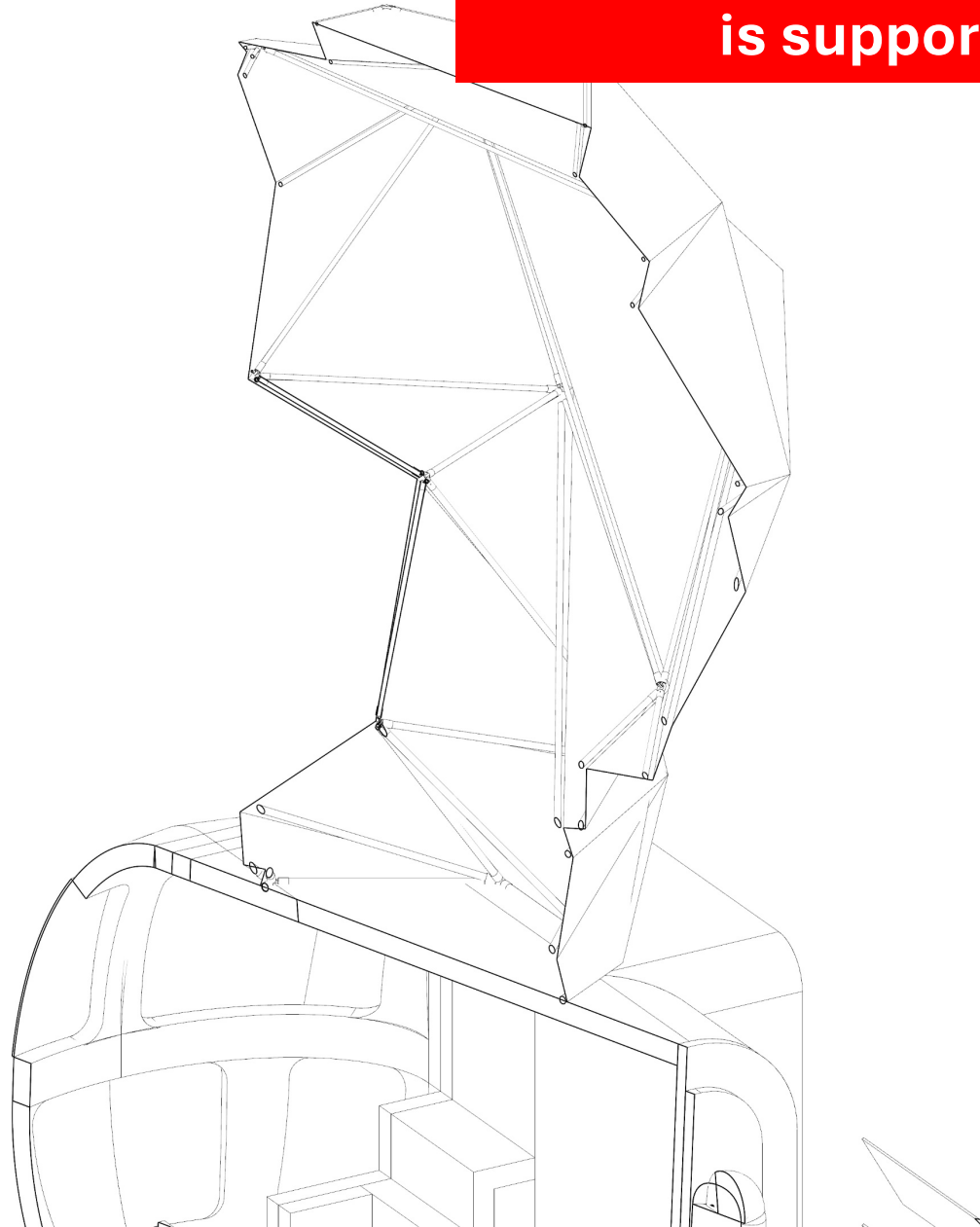
Explanation of how the cantilevered capsule
is supported by the structure

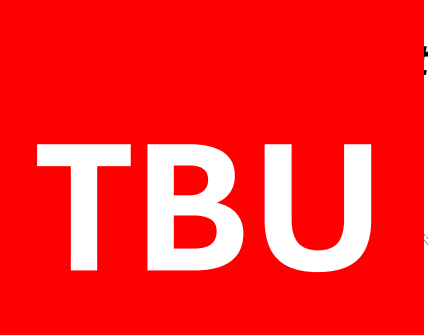


section

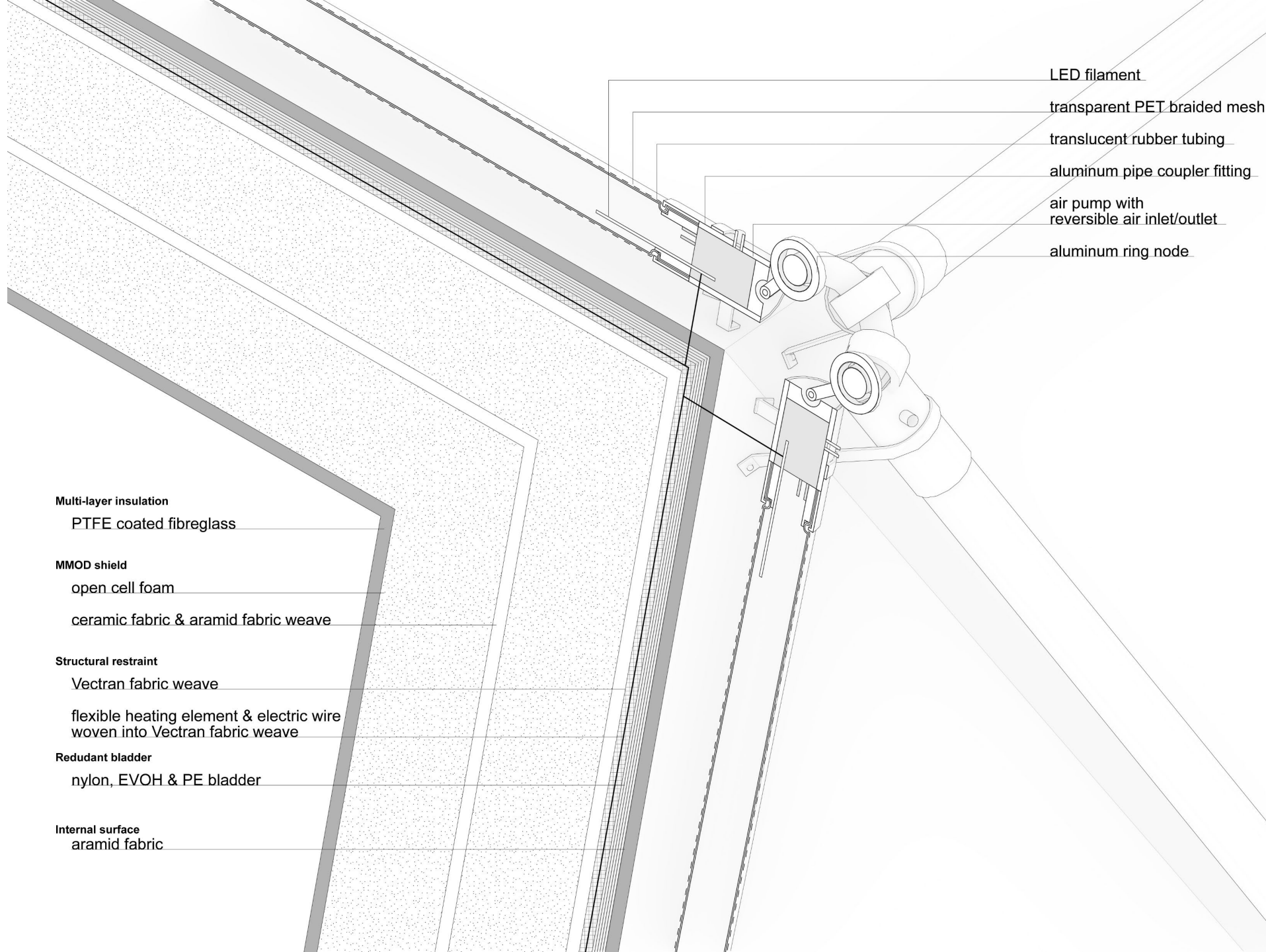
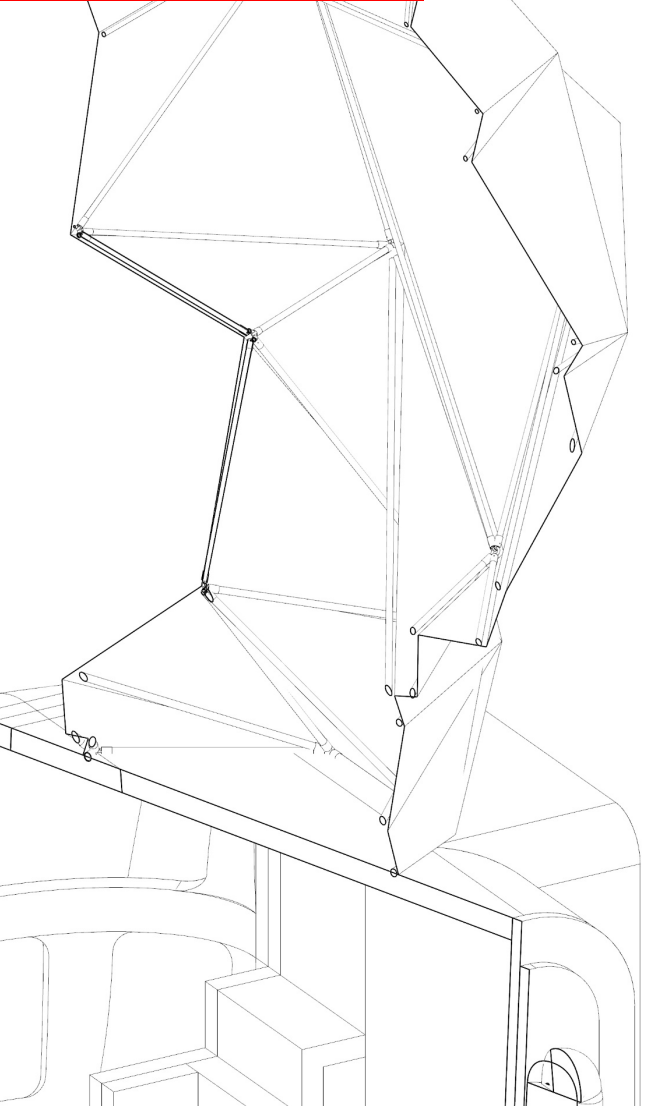
TBU

Explanation of how the cantilevered capsule
is supported by the structure





section



LED filament

transparent PET braided mesh

translucent rubber tubing

aluminum pipe coupler fitting

air pump with
reversible air inlet/outlet

aluminum ring node

Multi-layer insulation

PTFE coated fibreglass

MMOD shield

open cell foam

ceramic fabric & aramid fabric weave

Structural restraint

Vectran fabric weave

flexible heating element & electric wire
woven into Vectran fabric weave

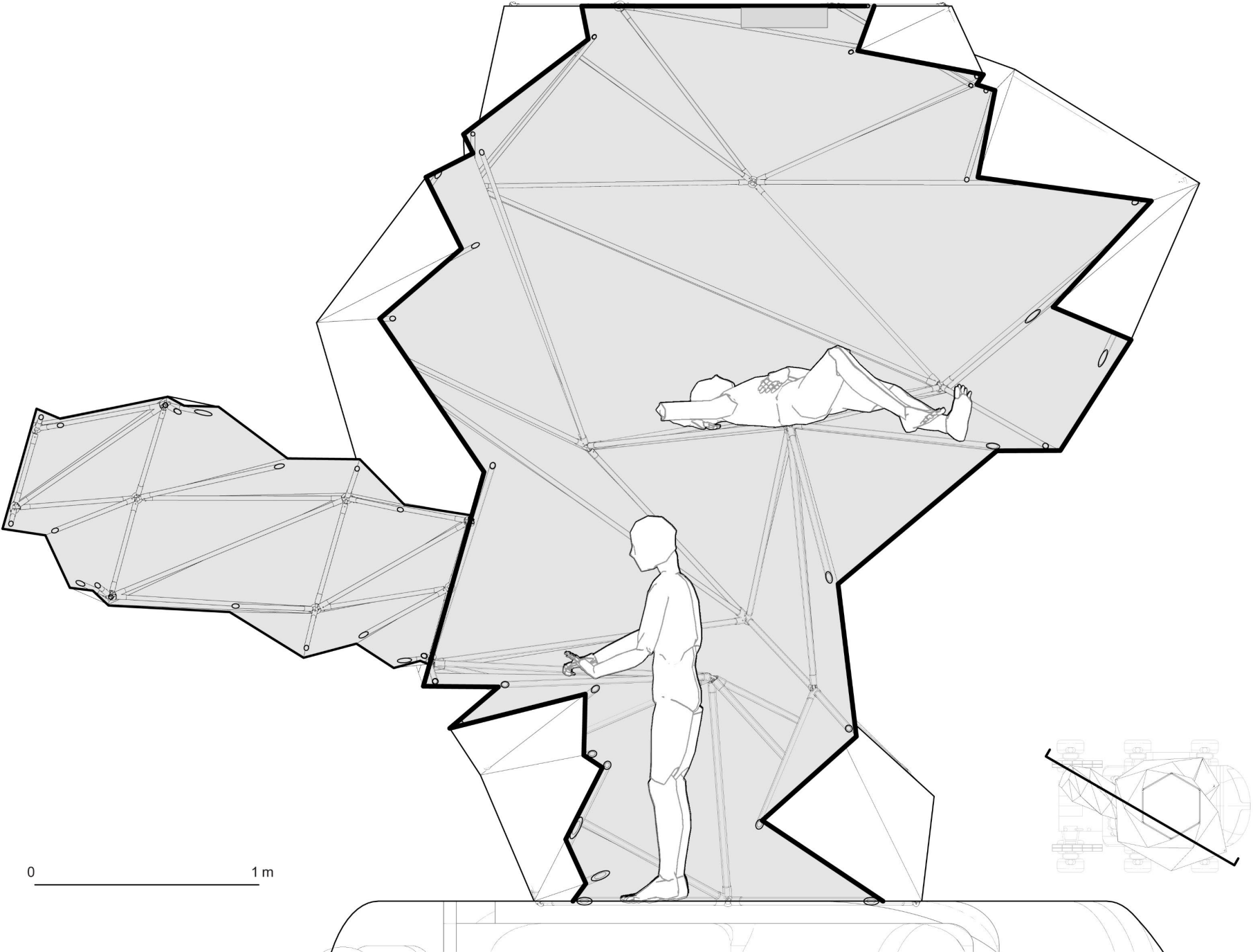
Redundant bladder

nylon, EVOH & PE bladder

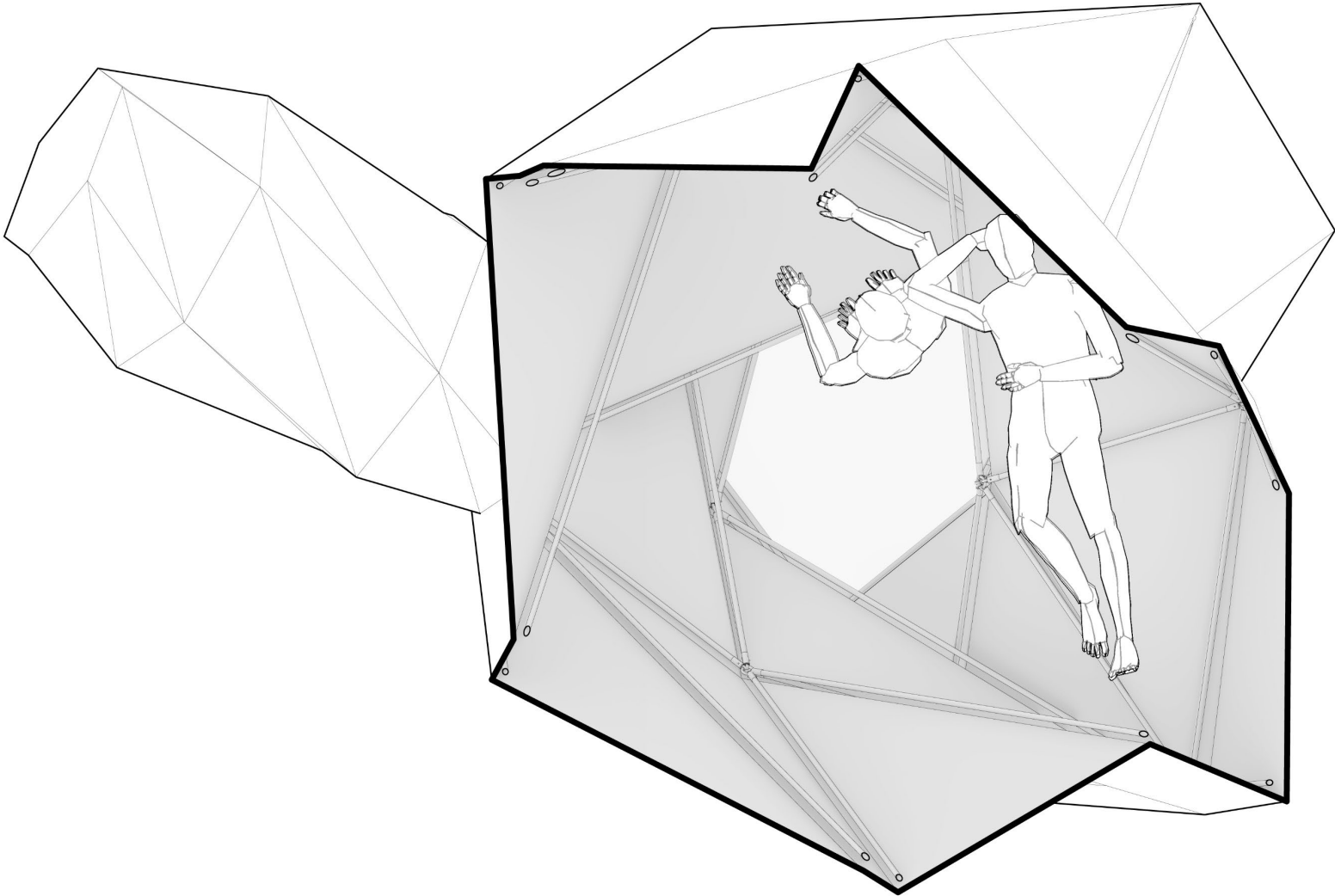
Internal surface

aramid fabric

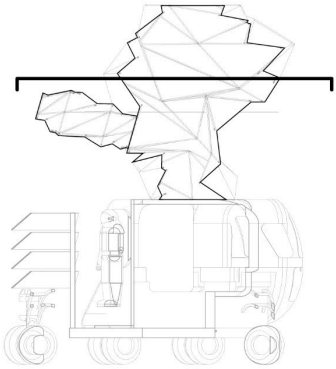
Section



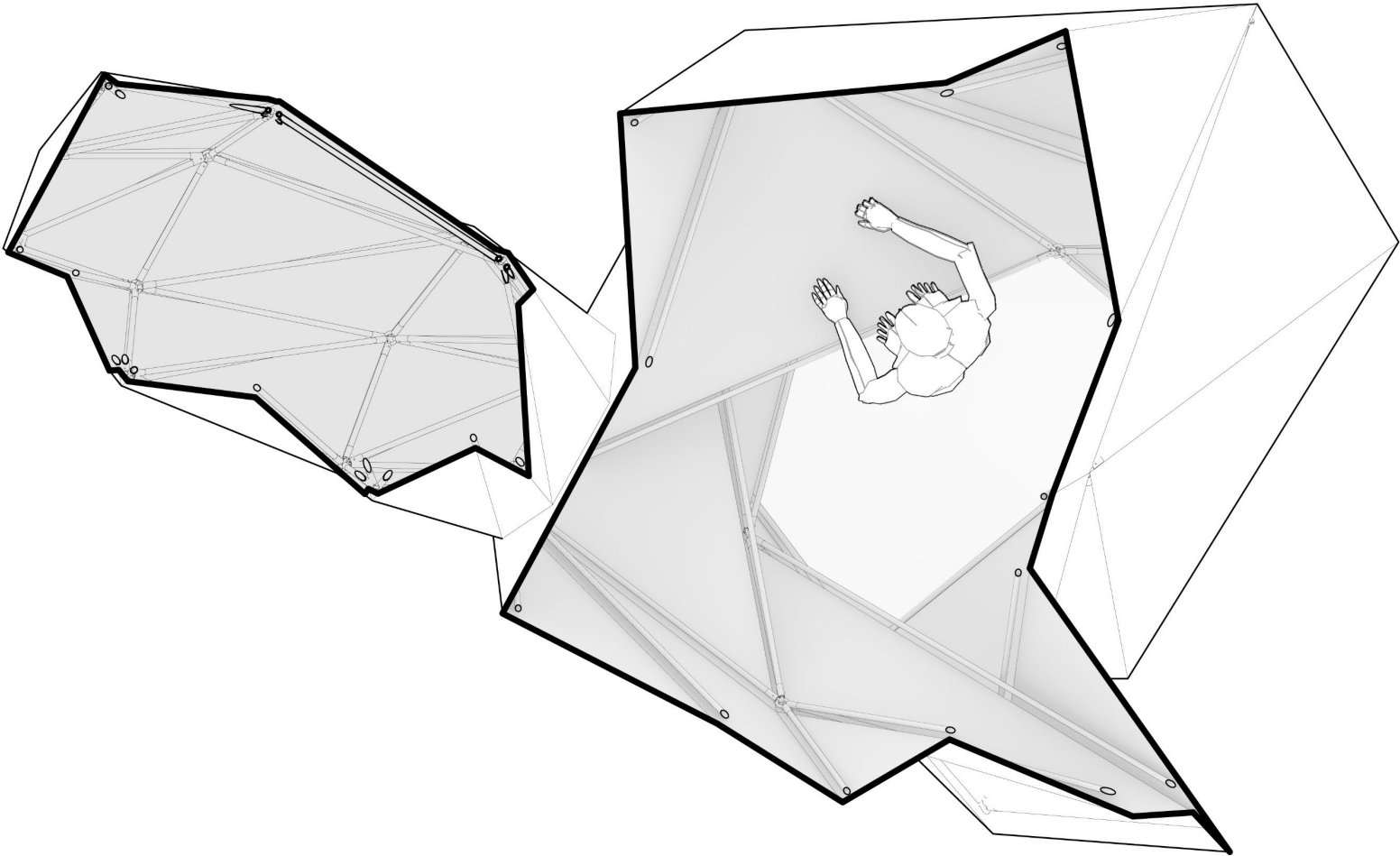
Plan Upper Level



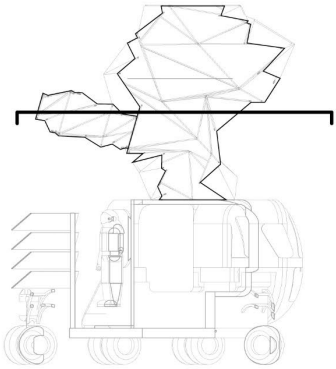
0 1 m



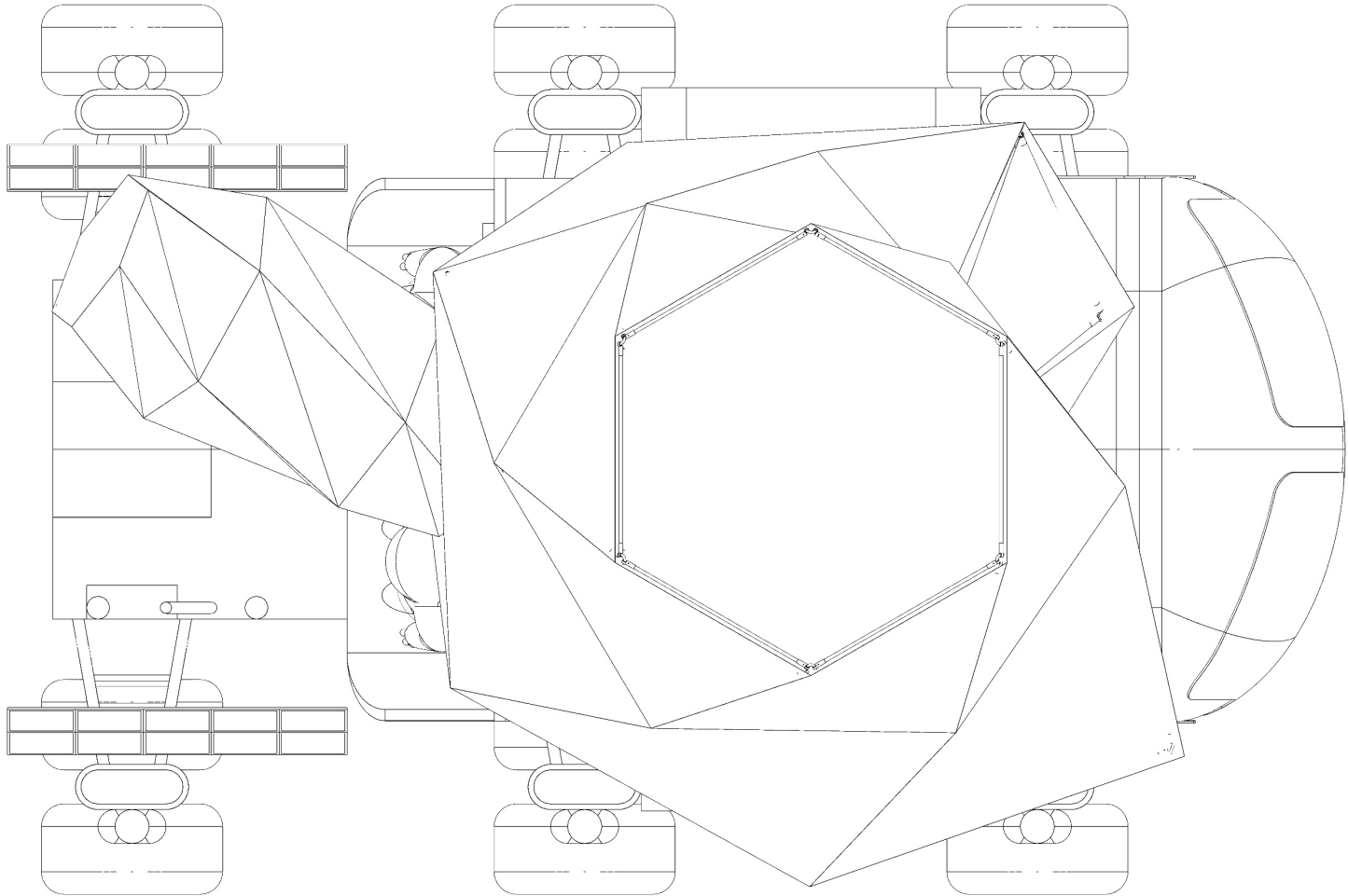
Plan Lower Level



0 1 m



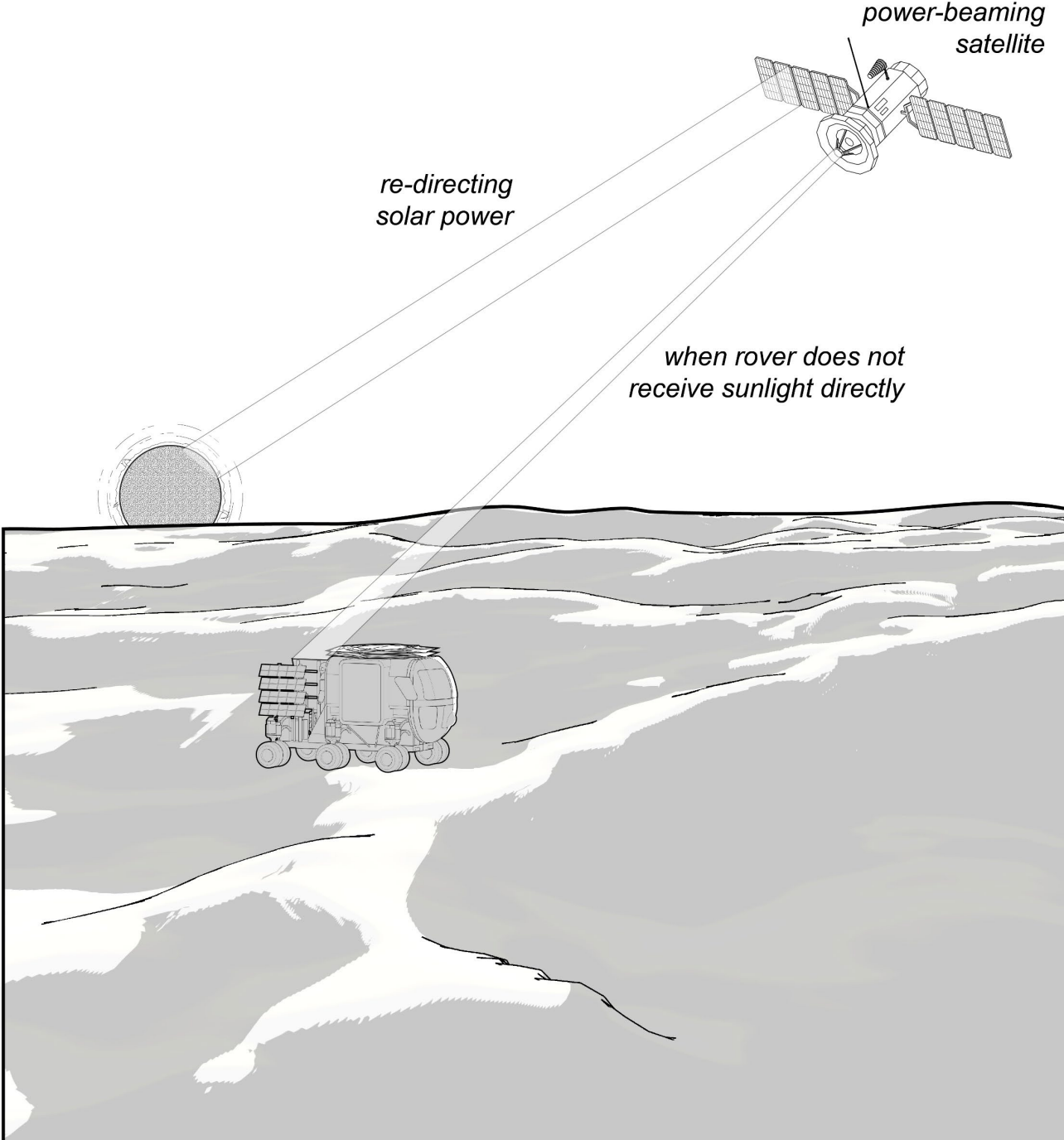
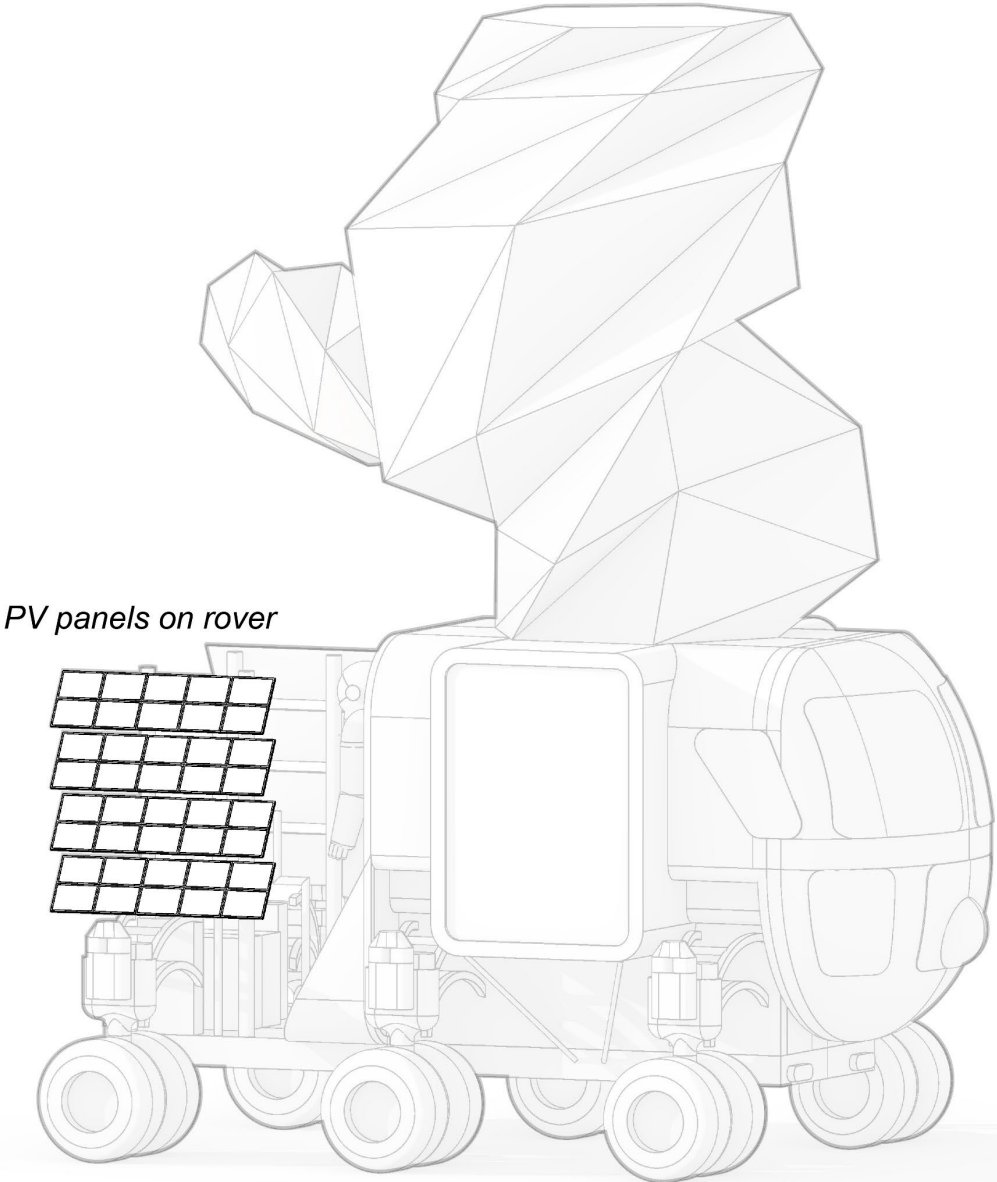
Roof Plan

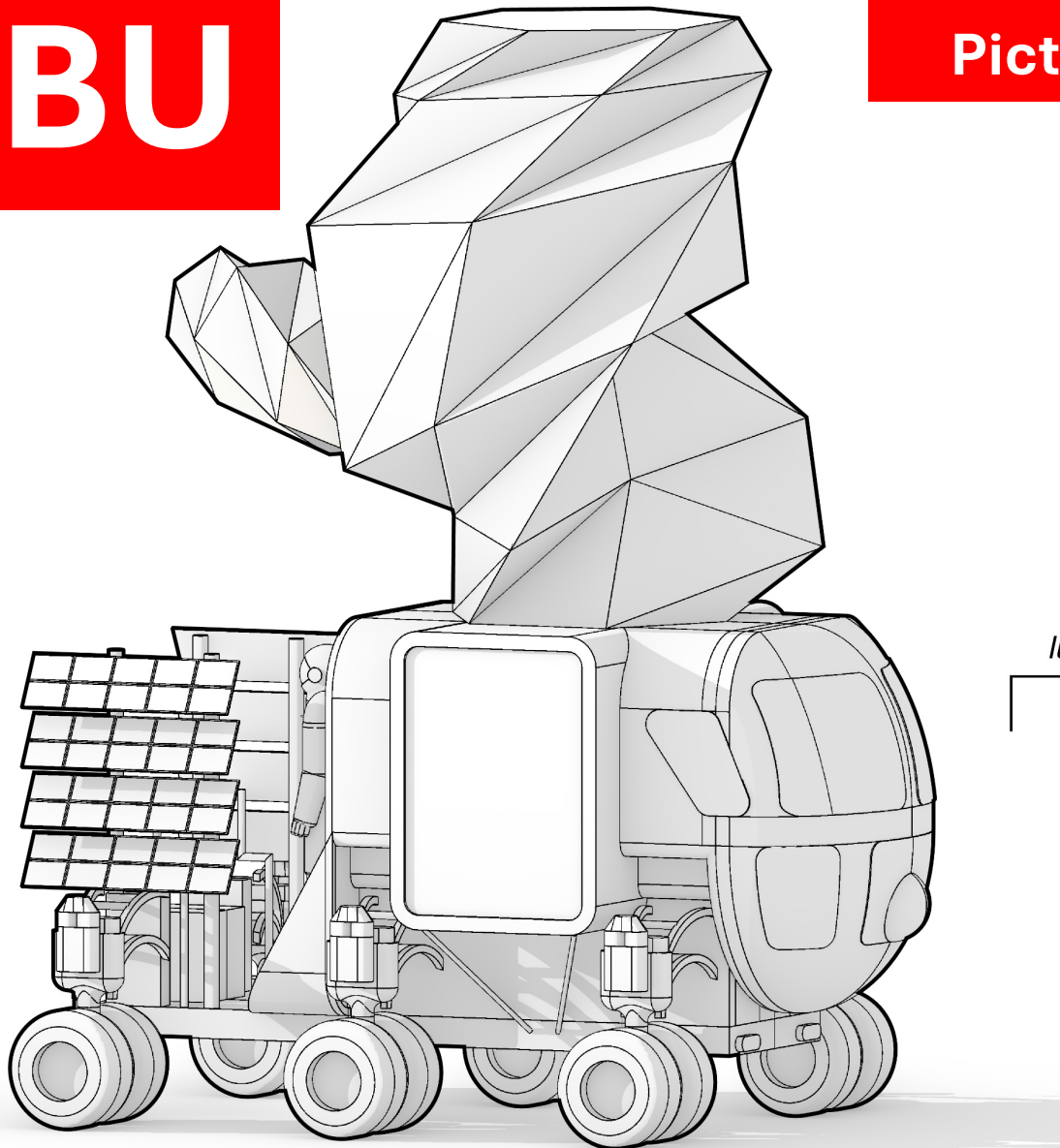


0 1 m

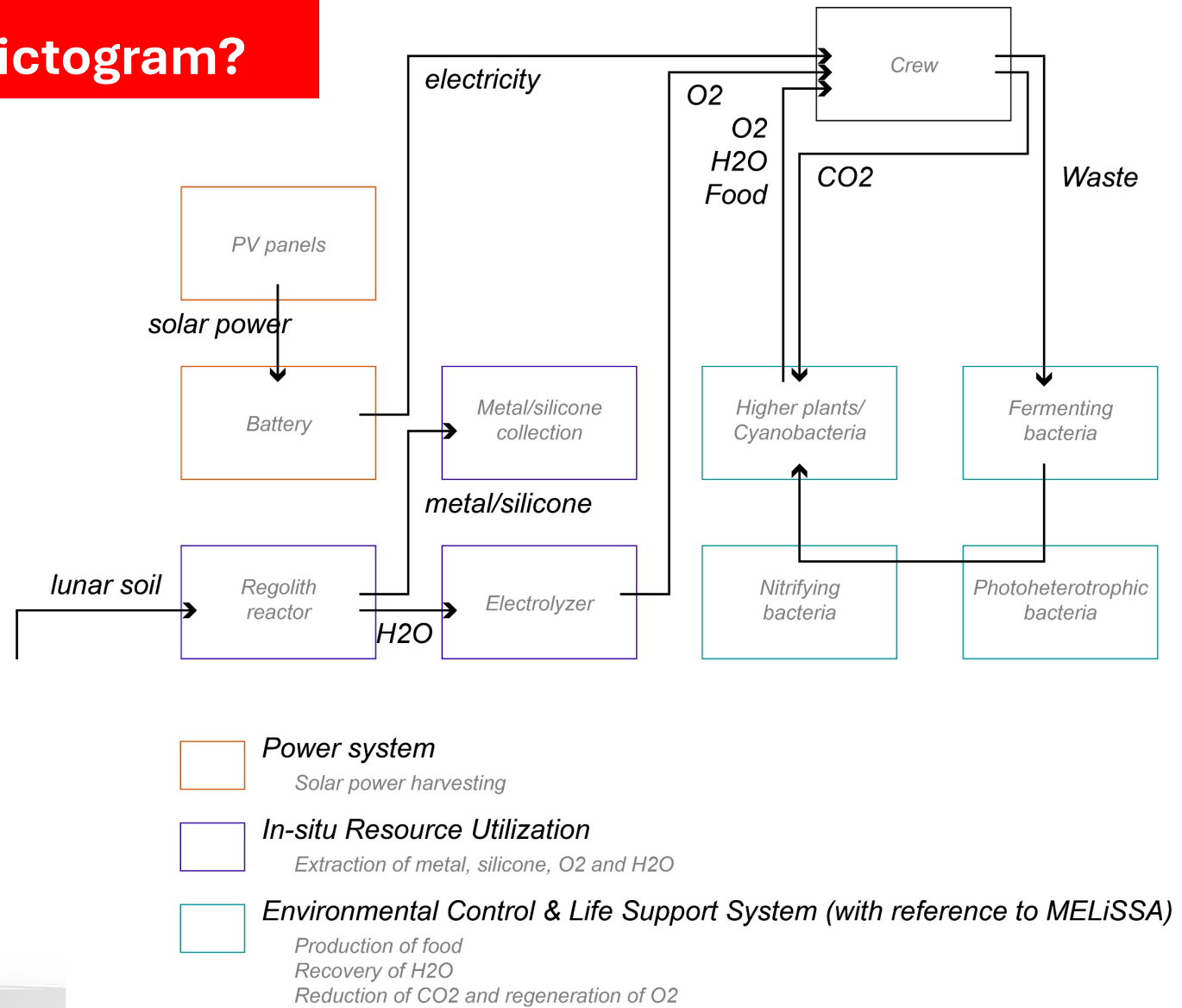
ECLSS and ISRU

Power supply

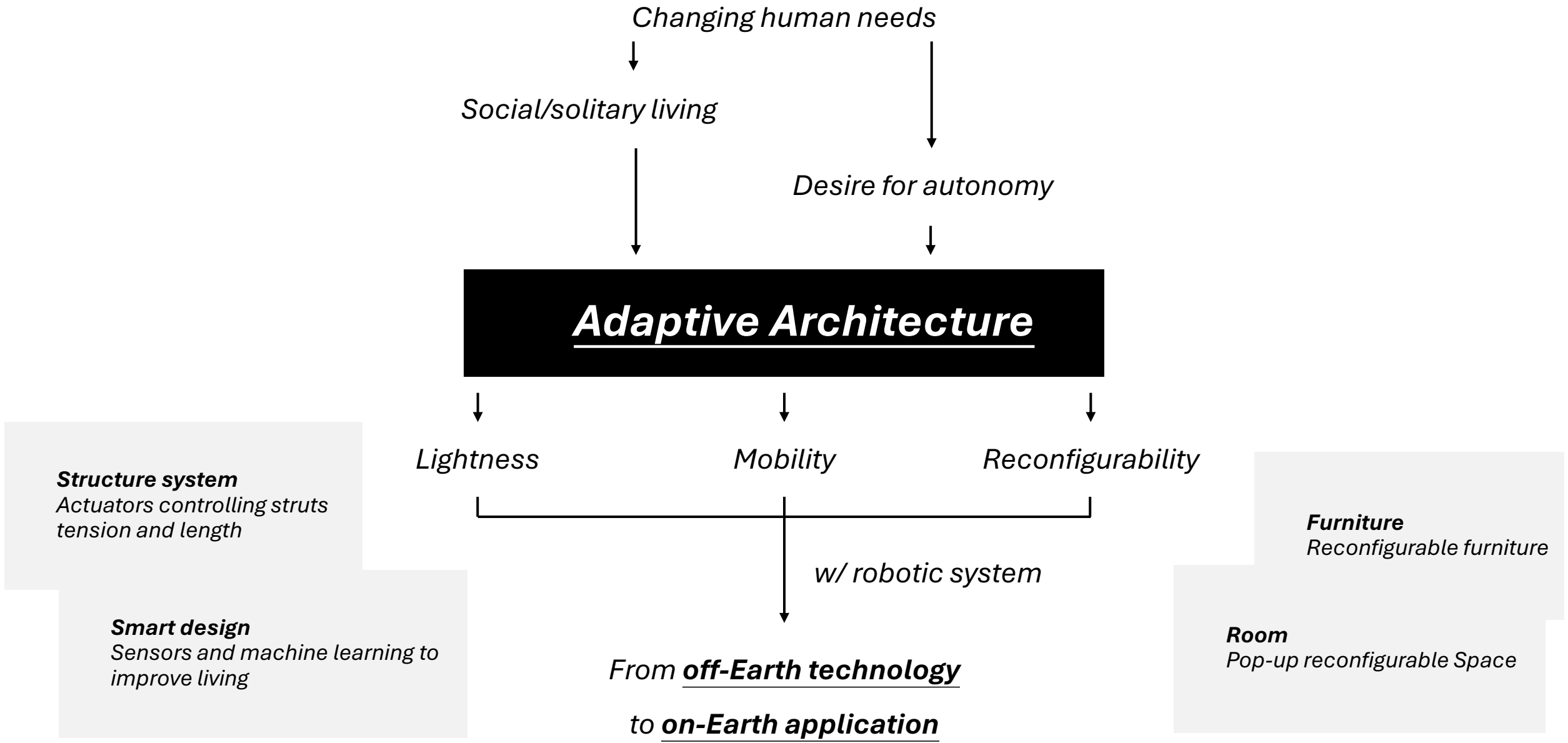




Pictogram?

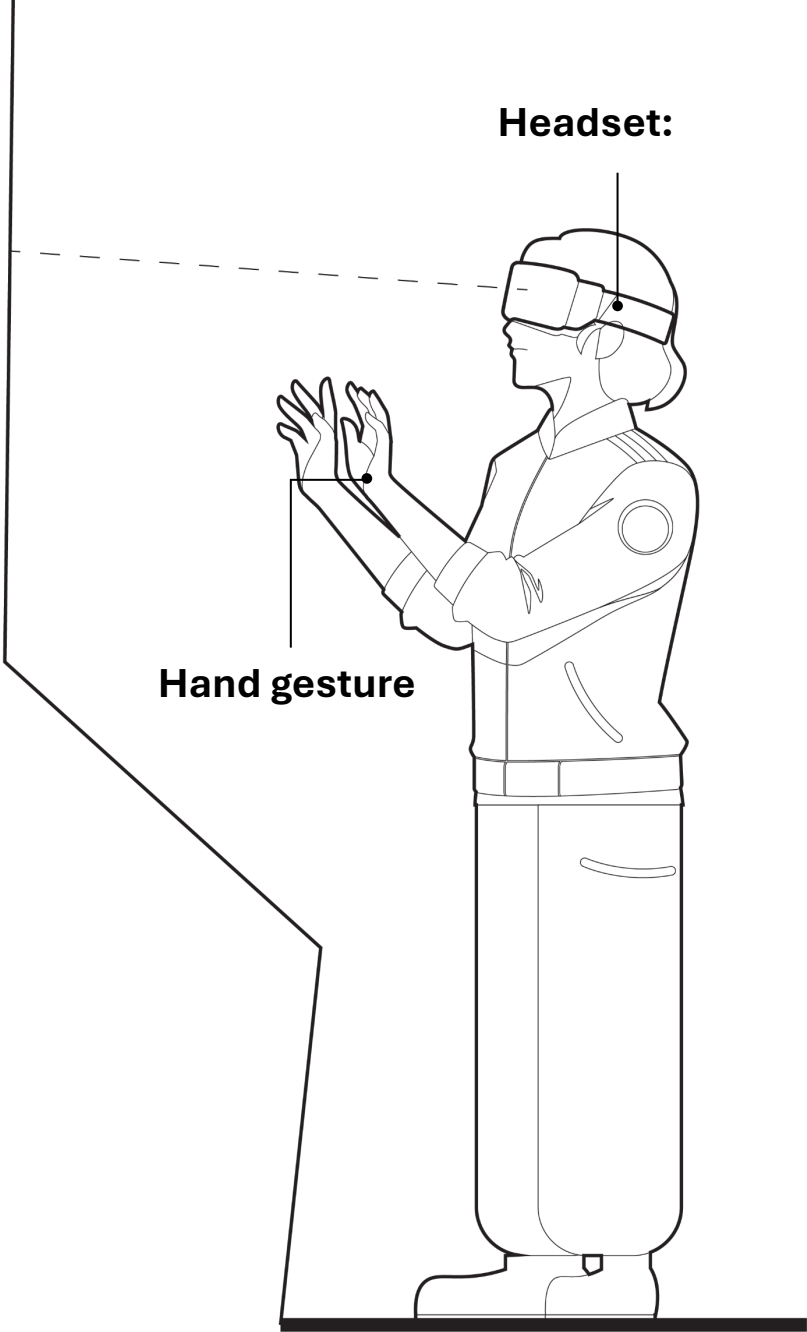
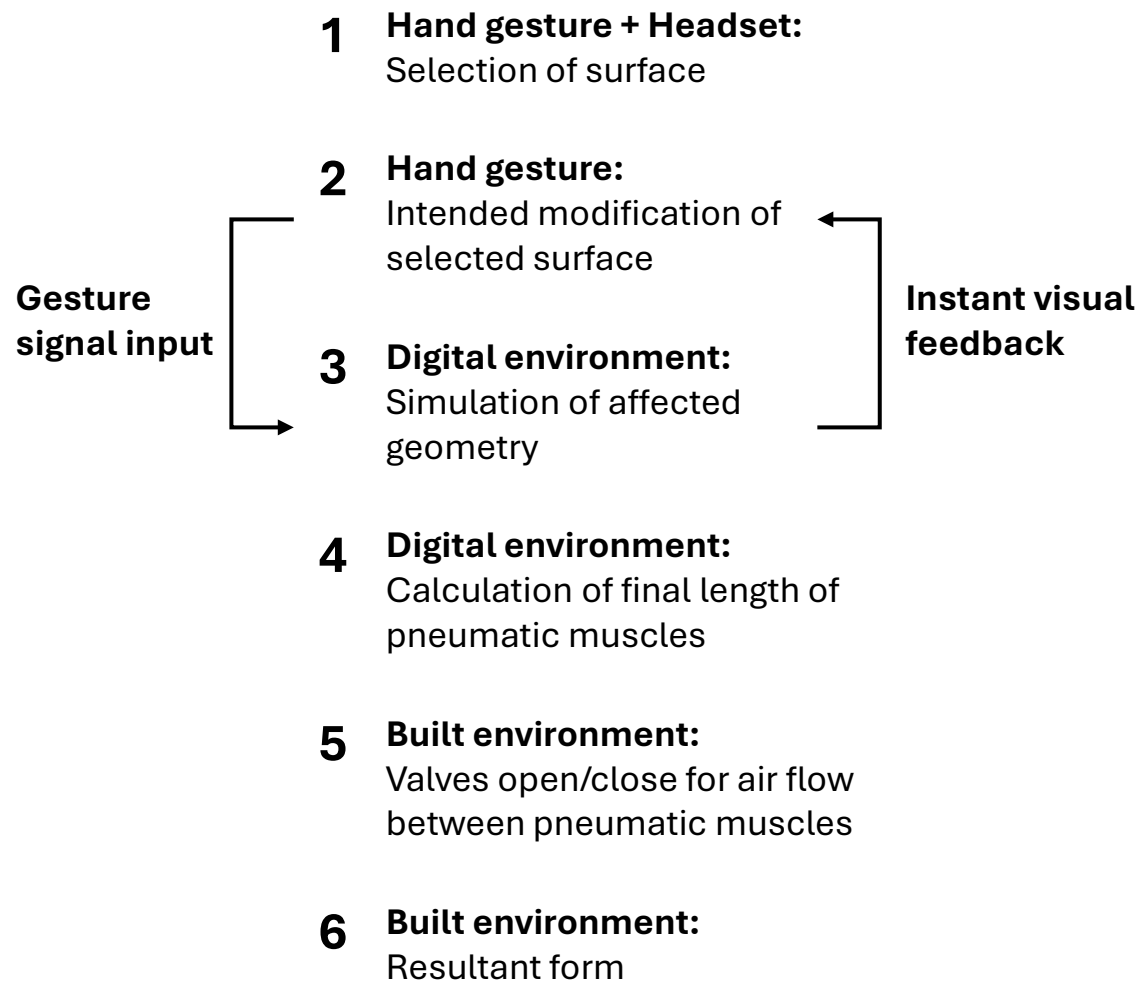


Relevance with on-Earth architecture



Potential Future Development

Augmented Reality Reconfiguration System



Transformed space in different scenarios

Augmented Reality Reconfiguration System

1 Hand gesture + Headset:
Selection of surface

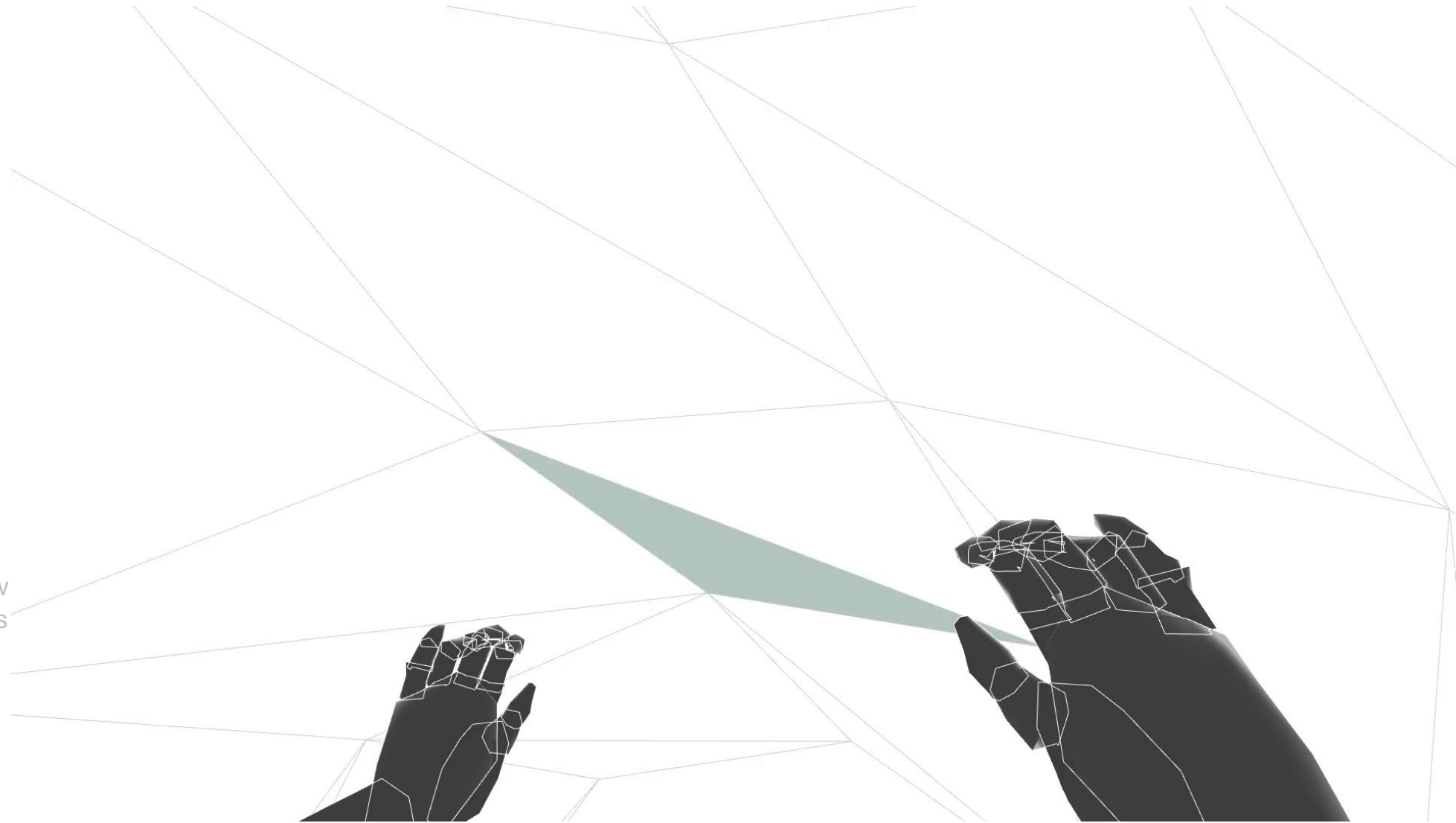
2 Hand gesture:
Intended modification of
selected surface

3 Digital environment:
Simulation of affected
geometry

4 Digital environment:
Calculation of final length of
pneumatic muscles

5 Built environment:
Valves open/close for air flow
between pneumatic muscles

6 Built environment:
Resultant form



Transformed space in different scenarios

Augmented Reality Reconfiguration System

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Selection of surface

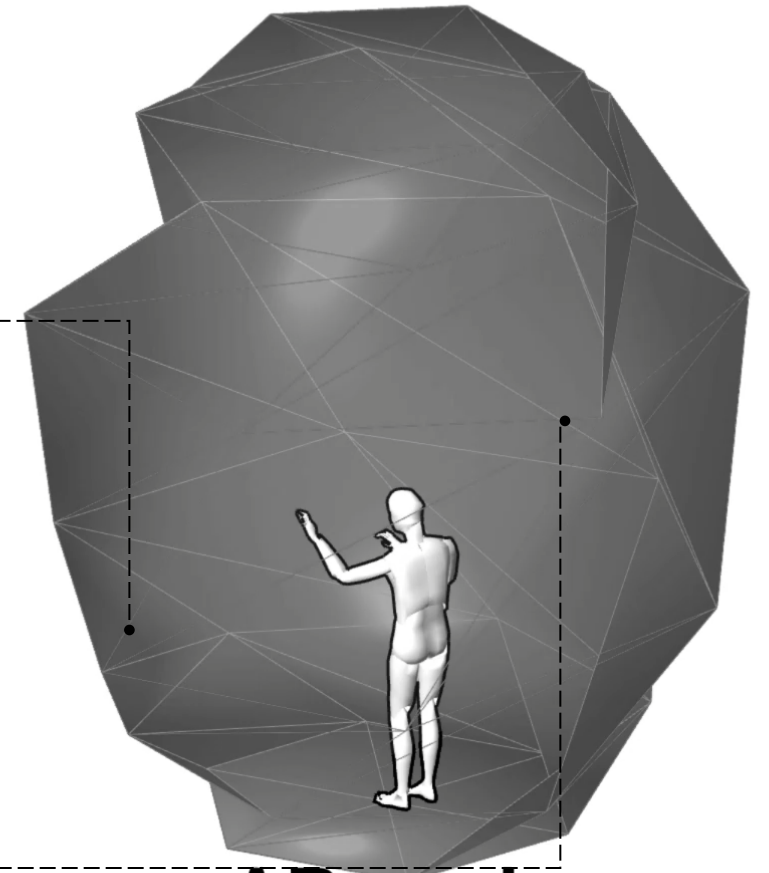
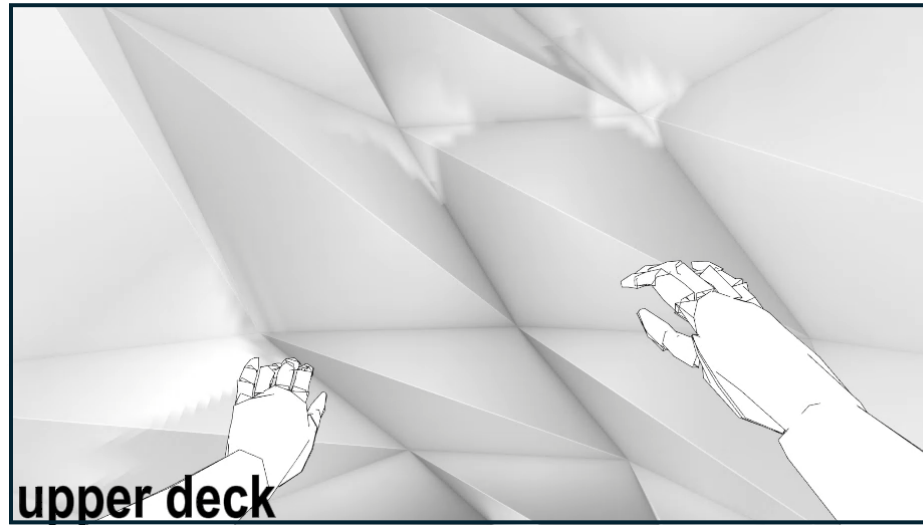
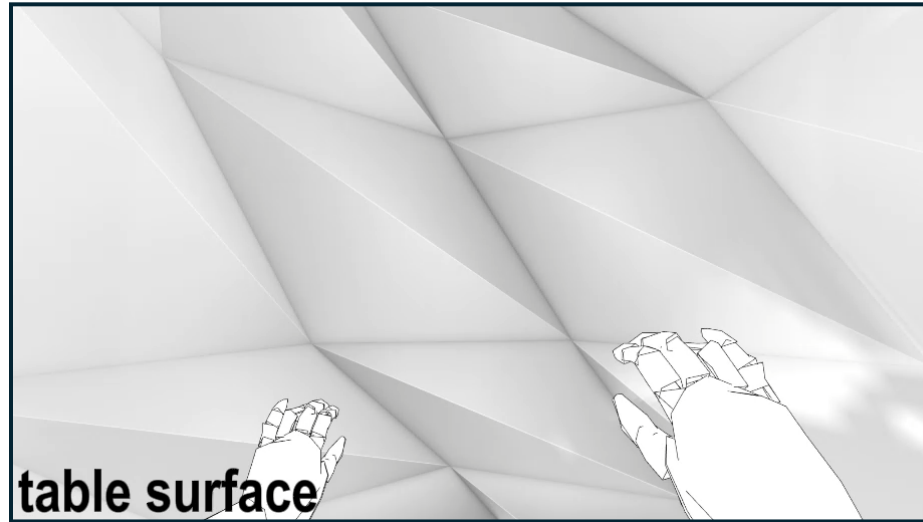
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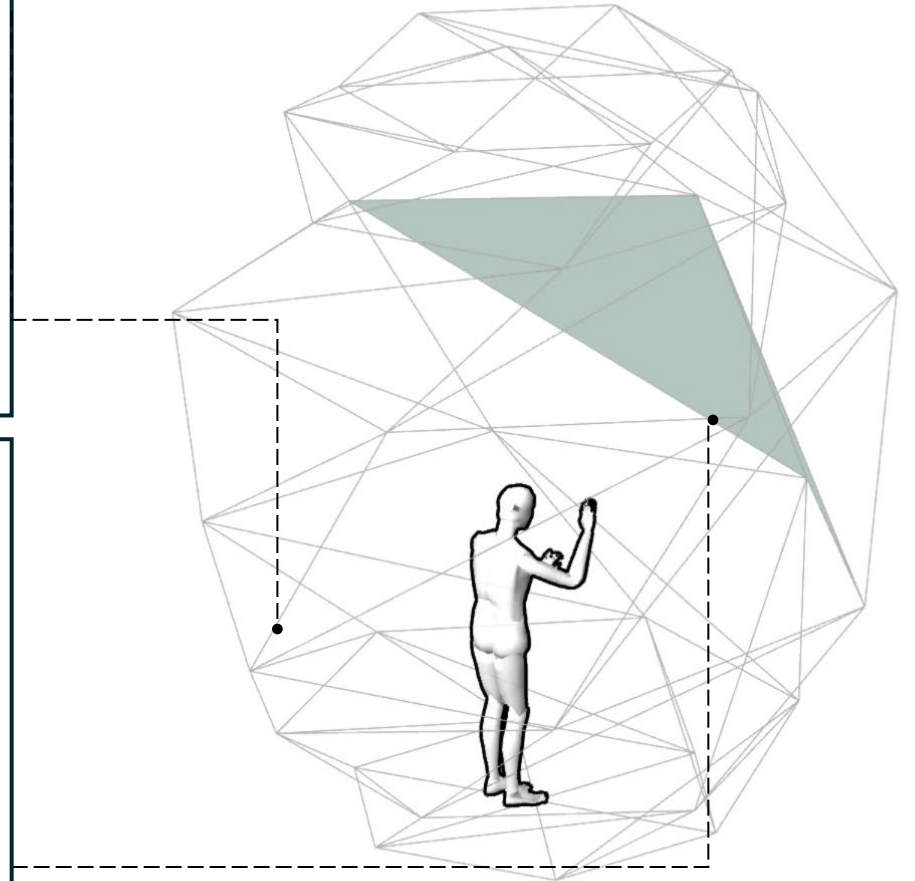
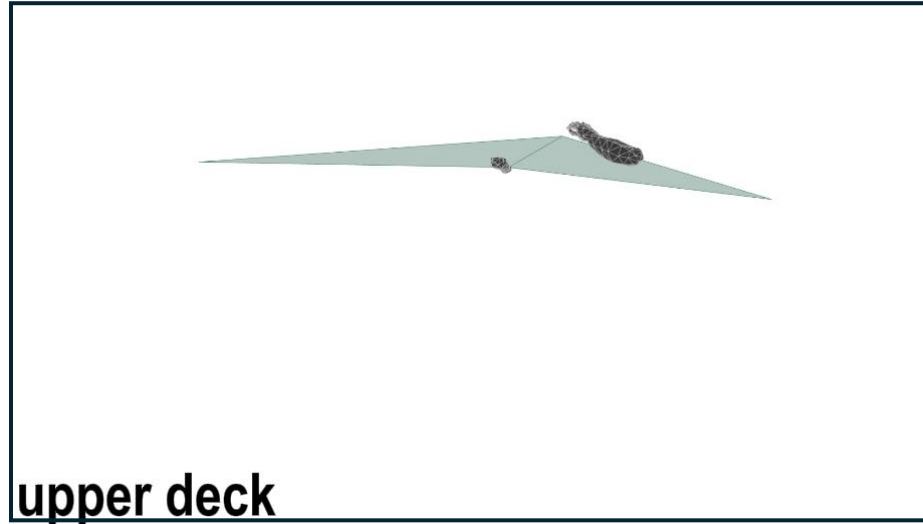
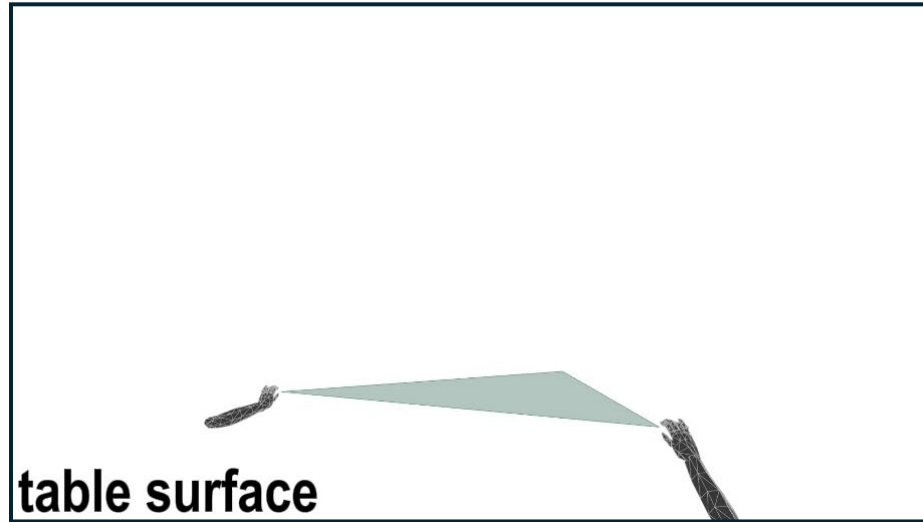
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