Swarm Habitat: Lava Tube Base Design with Non-Orthogonal Modular Coordination of The Truncated Octahedral Modules

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Swarm Habitat is a concept for building a long-term, rational lunar base inside the lava tube, which has been pointed out as highly habitable but has been little explored. The development of a permanent base involves two types of issues: interior design issues, such as a comfortable interior for the long-term crew and a translation paths of travel that facilitates movement and emergency evacuation even in low gravity, and architectural scale issues, such as ease of construction in an unexplored area and transportation from the landing zone to the construction site.This paper attempts to solve these two problems by using modules that can reconfigure themselves autonomously and cooperatively like Swarm and their modular coordination.Swarm Habitat is designed from the perspective of the shape of the module and the interaction of its configurations. The orthogonal configuration of cylindrical modules, which has been used in many previous studies, is not suitable for construction in a 3-dimensional terrain of a lava tube, due to the increased exposed area, difficulty in transportation to the site, and difficulty in moving the interior space under lunar gravity. Therefore, a module with the truncated octahedron is adopted as a module shape that is more like a sphere, which is easy to roll and can be connected in multiple directions in a non-orthogonal manner.The four modules, the smallest in configuration, "crawl" around the terrain by changing their configuration, "slide" into the lava tube, and "flock" together to form the final module. The final 100-module base is constructed by "combining" them. The non-orthogonal configuration allows the crew to jump and move through pressurized space.The mainstay of Swarm Habitat is that it can establish modular coordination while sequentially adapting to the lunar gravity environment and the irregular site.

Nomenclature

LZ	=	Landing Zone
LM	=	Lunar Module
MMOD	=	Micrometeoroid & Orbital Debrites
ISS	=	International Space Station
EVA	=	Extravehicular activity
ECLSS	=	Environmental Control and Life Support System
MMH	=	Marius Hill Hole

I. Introduction

With the recent humanned space program, including the Artemis Campaign, human exploration of the Moon will likely become more advanced after 2024.[1]In addition, spacecraft with large payloads, such as SpaceX's Starship, which is designed to send 100 people into lunar orbit,[2] are also emerging.For a variety of use cases such as

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research, tourism, etc., and long-term habitation on the Moon at the level of a few dozen people, the authors propose the Swarm Habitat building module.This space architecture approach takes a standard truncated octahedron module as the keystone unit and aims to form a base for dozens of people in the Lava tube, which has been attracting attention in recent years for its high habitability, while forming a modular coordination-like Swarm, with these units cooperating with each other autonomous and cooperative manner. The goal of the project is to build a base for dozens of people in a Lava tube, which has attracted attention in recent years for its high habitability.The truncated octahedron module is compactly housed in the payload fairing during launch, thanks to its inflatable structure. The module will be placed on the lunar surface at the surface landing site.After arriving at the lunar surface landing site, the four modules will change their configuration and roll over the irregular terrain to explore the lunar surface.Further modules can be combined with the minimum configuration of four modules to form a lunar base with a larger total capacity, like the ISS, and a huge habitable area as a "Swarm" of 100 modules.Although the truncated octahedron architectural shape has not been widely used in previous studies, this paper proposes that the truncated octahedron is superior to the previously proposed cylindrical module from the following points.

A) The number of bonding planes is large and the bonding directions are multidirectional.
B) Large volume per surface area and "approximately to a sphere" shape.
C) close packing of space in a single shape is possible.
D) Easier to roll, making it easier to place the module itself on irregular, three-dimensional terrain.

The above advantages make the truncated octahedron module superior for construction in three-dimensional terrain, especially in lava tubes, which have recently been recognized for their high habitability.The truncated octahedron assumes non-orthogonal connections.Cylindrical modules, such as those used in the ISS, are designed to resemble a cube in pressurized space and are assumed to have a orthogonal module configuration.In contrast, the non-orthogonal modular coordination of the truncated octahedron allows for the establishment of translation paths and interiors that are adapted to the lunar gravity environment.Another advantage of the truncated octahedron is that it is spherical and has a maximum of six rotational symmetries.Because it rolls more easily, the truncated octahedron can swarm over the irregular terrain of the Moon like a pill bug.

Section II introduces previous research on orthogonal modular coordination and discusses the concept of autonomous and cooperative lunar bases required for a lunar base.In Section III, the superiority of the truncated octahedron as a module shape is discussed in comparison with other shapes.Section IV introduces the construction method of specific modules, autonomous movement methods, and architectural details.Section V describes the process of combining 100 modules and Section VI discusses future issues.

II. Literature Review

For a lunar base that is expected to be developed over a long period, it would be desirable to send in a series of new modules and expand them each time to accommodate scale expansion and changes in use cases. In this case, it is preferable to use modules while reconfiguring them according to their use cases. In this paper, we would like to emphasize that even a less explored, unknown, and irregular site like the lava tube can be used to build a habitat for dozens of people through modular coordination. In this chapter, we survey and introduce previous studies on the shape of modules and their configuration schemes in a lunar base. In the survey, we focus on the shape of the module, the configuration method, the construction method, and the interior. In addition, some of the early lunar surface projects, such as Project Horizon and Zvezda, have horizontally cylindrical modules arranged in series or circuits[6]. The survey in this paper eliminates such 2D plans and assumes a 3D plan that includes vertical movement. Also mention the advantages of Mobile base for autonomous mobility.

A. Orthogonal Modular Configuration

Bannova discusses modular coordination for orthogonal placement of modules of the same type as those in operation in the space program. [7]Figure 1 shows this plan. Horizontal modules are configured in a crisscross configuration, which is expanded by adding more modules. The cross-shaped modules can be arranged flexibly about the terrain, and by adding modules in a circuit-like configuration, two directions of evacuation can be secured. Vertical modules have horizontal floors arranged in a hierarchy, just as in architecture on Earth. This kind of modular coordination can be seen in Project Olympus[8], Moon Village[9], and other lunar base studies that have been presented since the announcement of the Artemis Campaign, and is a kind of paradigm.

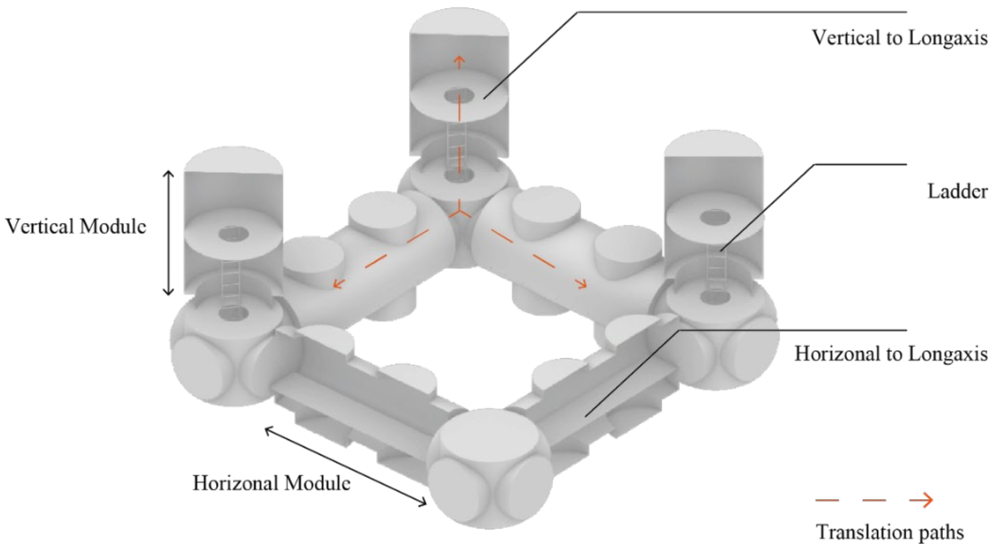


Figure 1. 3D view of orthogonal modular coordination.

For such orthogonal arrangements, ladders or stairs have been proposed as a method of vertical movement inside the pressurized space. Ladders, in particular, do not occupy much floor space. Moreover, ladders, as a means of transportation that involves a hand-grasping motion, appear to have an advantage on the moon's surface, where frictional forces are low. However, ladders are not suited for moving while holding an object. Also, it is difficult for humans to pass each other on a ladder.

B. Mobile Base

There are three main advantages of a mobile base.[10] One is the distance between the LZ and the habitation zone: once the habitation zone is completed, no rocket can take off and land within a few kilometers of it due to the risk of collision with rocket ejecta and explosives. Another problem is that of construction equipment. In the case of a static module, the forklift and other heavy equipment necessary for its construction must also be transported.By incorporating landing and moving mechanisms into the module itself, it would be possible to reduce the number of rockets carried. A final advantage of a mobile base is the exploration capability.A pressurized rover would allow manned exploration on a multi-day basis, extending the range of exploration. In addition to these, an autonomous mobile rover would be able to scan the ground, find a safe location, and anchor itself there, which would be a construction method. This is a seamless method of checking the safety of the site, transporting the building units, and erecting them.This is especially promising for unexplored terrain such as Lavatube, which has the potential to establish large settlements.

C. Swarm Robotics

In order to establish reasonable modular coordination to cope with the lunar gravity environment and unexplored and unshaped sites, standard modules need to move autonomously and build themselves while maintaining the coupling of the pressurized space among themselves.A study of Swarm robotics with capabilities similar to those described above is A freeform strut-node structured MSRR system (FreeSN) by Tu et al.[11] In this system, a self-propelled modular robot with a Freeform Connector lifts a sphere larger than itself and moves in a group of multiple swarms that self-assemble with each other (Figure 2).An important aspect of this Swarm robotics technology is that the module bodies assemble and move in a rolling manner to overcome terrain larger than themselves. Such technology is also attracting attention in the field of space architecture, [12]where materials are difficult to transport, sites are not well-cleared, and unexpected events are likely to occur. Swarm Habitat is proposed based on the existence of such technology.

Figure 2. The process of FreeSN self-assembly. Image Credit: Yuxiao Tu et al.(2022) [11].

Swarm Habitat uses a construction method in which newly arrived modules are added to a flock of several already-built modules. The modules in Swarm Habitat are not simply building units, but rather hardware for movement. This design concept may be particularly effective in low-gravity environments such as the Moon. On Earth, when erecting an architectural structure, it is possible to anchor the building components to the ground, an entity with great inertia. This allows for the stable construction of large structures on the earth. However, in orbit or on the Moon, the ground may not exist, or if it does exist, it may not be satisfactorily surveyed and therefore unreliable. A swarm habitat can be seen as "an entity that has greater inertia than itself and can more easily anchor itself than the ground" for the newly added module. This allows for stability in "unreliable ground" that has not been well explored, such as the lava tube.

III. The Truncated Octahedron Concept

The truncated octahedron is a polyhedron consisting of eight hexagons and six quadrilaterals for a total of 14 faces. The truncated octahedron is formed by truncating 1/3 of the length of each side from the six vertices of the regular octahedron so that each side has the same length. In addition to the truncated octahedron and the regular octahedron, the authors compare the cube and the rhombic dodecahedron as candidates for the module shape, as polyhedra that can be Close Packed as well. The following three items will be compared.

A. Number of Faces

In this paper 1) Proposed method of movement and interior design within a pressurized space suitable for the lunar gravity environment. 2) Modular coupling with a high degree of freedom 3) Non-orthogonal module coupling from the viewpoint of mobility in multiple directions. Regarding the coupling method, ISS modules have two front-to-back interfaces (i.e., the Destiny) and six directional interfaces (i.e., the node module), front-to-back, up-and-down, and left-to-right. It is a means to connect modules in series and to connect modules that also have interfaces in orthogonal directions, such as the node module, to change directions, thereby allowing them to be coupled and moved in multiple directions. In contrast, the truncated octahedron can open interfaces in eight directions using only its hexagonal faces. This means that it can move in more directions than a cylindrical shape, which translates to easier evacuation in a pressurized space. Also, as mentioned in Section II, cylindrical modules can only be placed horizontally or vertically on the ground, which has limited the location and topography of their placement. In the case of the truncated octahedron, however, it is composed of a total of 14 hexagonal and quadrilateral faces. As long as even one of these faces is in contact with the ground, it can be constructed in that location, and it can be said that this shape is easier to construct than the cylindrical shape in that it does not take up much space. This feature is effective not only in terms of ease of installation of the module but also when the module is viewed as a moving body. The stable center of gravity and the fact that there is no difference in the area of the ground surface during rotation means that the rolling friction is smaller and the module can roll more easily.

B. Approximation to Sphere

In a sense the most ideal Swarm Habitat module shape is a sphere. First, the sphere has the smallest volume-to-surface area (S_v). A small volume-to-surface area reduces the risk of exposure to MMOD and radiation, and allows for a larger pressurized space inside. In addition, space structures with smaller masses are easier to transport because they consume less fuel during launch. The mass of the pressurized module is obtained by Eq. 1. [14]

$$M = 13.94(A)^{1.15} \tag{1}$$

M is mass , A is the surface area, and the smaller the value, the lighter the mass; the S_v entry in Table 1 is the volume-to-surface area for each shape when the length per side is a. This value is the smallest for the truncated octahedron. Next, we compare the ease of rolling (ease of rotation) of the module as a moving body. One of the items is rotational symmetry. Rotational symmetry is the property that a certain shape looks the same even if it is rotated about a certain axis. It is determined by whether a solid overlap exactly when it is rotated n times (n is an integer greater than or equal to 2) around a certain axis. For example, a square has 360 / 90 = 4 is the order of n, since the figures overlap when rotated 90 degrees.A sphere is a shape with the highest rotational symmetry because the shapes overlap perfectly when rotated infinitely.The larger this value and the closer the shape is to a sphere, the easier it is to rotate. In Table 1, the object of rotation is compared from the three axes of the center of the face, the center of the edge, and the center of the vertex of each figure.As a result, the axes N_2 (the center of the hexagonal face) of the truncated octahedron overlap in 6 rotations, and this value is the largest.Next, we compare Sphericity, a measure of how close a sphere is to a spherical shape, with a sphere being 1. It is calculated by Eq. 2.[15]

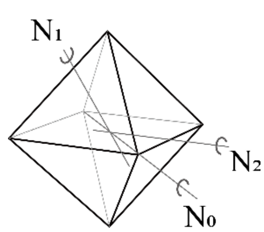
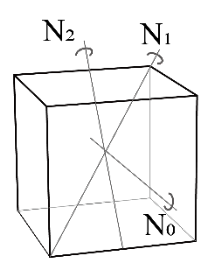
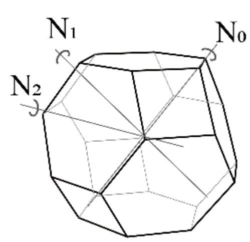
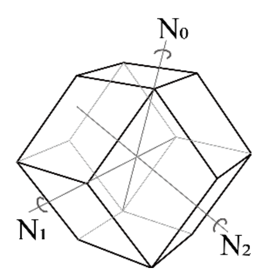
$$S = \pi^{1/3} 6V^{2/3}/A \qquad (2)$$

S is sphericity, V is the volume and A is the surface area. The truncated octahedron is 0.909, the largest and closest to the value of the sphere. Next is the existence of the circumsphere. circumspect is the sphere tangent to all vertices of the shape and determines the size of the payload fairing.In the case of the rhombic dodecahedron, the spheres passing through the six vertices, which are the vertices of the regular octahedron, and the eight vertices, which are the vertices of the cube, have different diameters and thus do not have circumscribed spheres and are therefore less likely to roll.

C. Close Packing

When multiple modules are combined for operation, as in Swarm Habitat, the exposure area can be reduced by stacking each shape without gaps. Cylindrical modules have the problem of inevitably creating gaps when they overlap. In addition, a single type of regular octahedron cannot be used for close packing, although it can be combined with other shapes such as tetrahedrons for close packing.Therefore, the regular octahedron is not suitable for modular coordination of single shapes.

Table 1. Comparison of regular octahedron, cube, truncated octahedron, and rhombic dodecahedron.

	Regular Octahedron	Cube	Truncated octahedron	Rhombic dodecahedron
Transparent				
Faces	8 triangles	6 squares	6 squares 8 hexagons	12 rhombus
S_v	≈ 7.35/a	≈ 6/a	≈ 2.36/a	≈ 3.67/a
Rotational symmetry	$N_0 = 4$ $N_1 = 3$ $N_2 = 2$	$N_0 = 4$ $N_1 = 3$ $N_2 = 2$	$N_0 = 2$ $N_1 = 4$ $N_2 = 6$	$N_0 = 4$ $N_1 = 3$ $N_2 = 2$
Sphericity	≈ 0.846	≈ 0.806	≈ 0.909	≈ 0.905
Circumsphere	○	○	○	x
Close packing	x	○	○	○

From the comparison of these items, it can be said that the shape that best meets the requirements is the truncated octahedron, which is the most suitable shape for the Swarm Habitat.

IV. Architectural Design & Construction Method

A. System Design

Figure 3 shows a 3D view of the modules that make up the Swarm Habitat. Docking interfaces are provided on the hexagonal faces of the truncated octahedron. Therefore, the Swarm Habitat is composed of hexagons of the truncated octahedron joined to each other.The interface is 2 m in diameter and is equipped with a Berthing Mechanism and a Rotatable Connector. The interface has a shutter that opens inward when viewed from the module. When the modules are connected to each other, the shutter opens inward to connect the pressurized spaces. When the shutters are closed, the interface is sealed. Since there are eight interfaces, there are always several areas that are not used for docking but are completely closed by the shutters to ensure safety. The shutters have small windows that can be used to let in outside light like a top light, for viewing, or for observation of the lunar environment.The interface is fitted with Folding legs facing outward on the outer shell. This mechanism acts like a claw that grips the terrain.They are folded outward to prevent them from getting in the way when the modules are joined together.

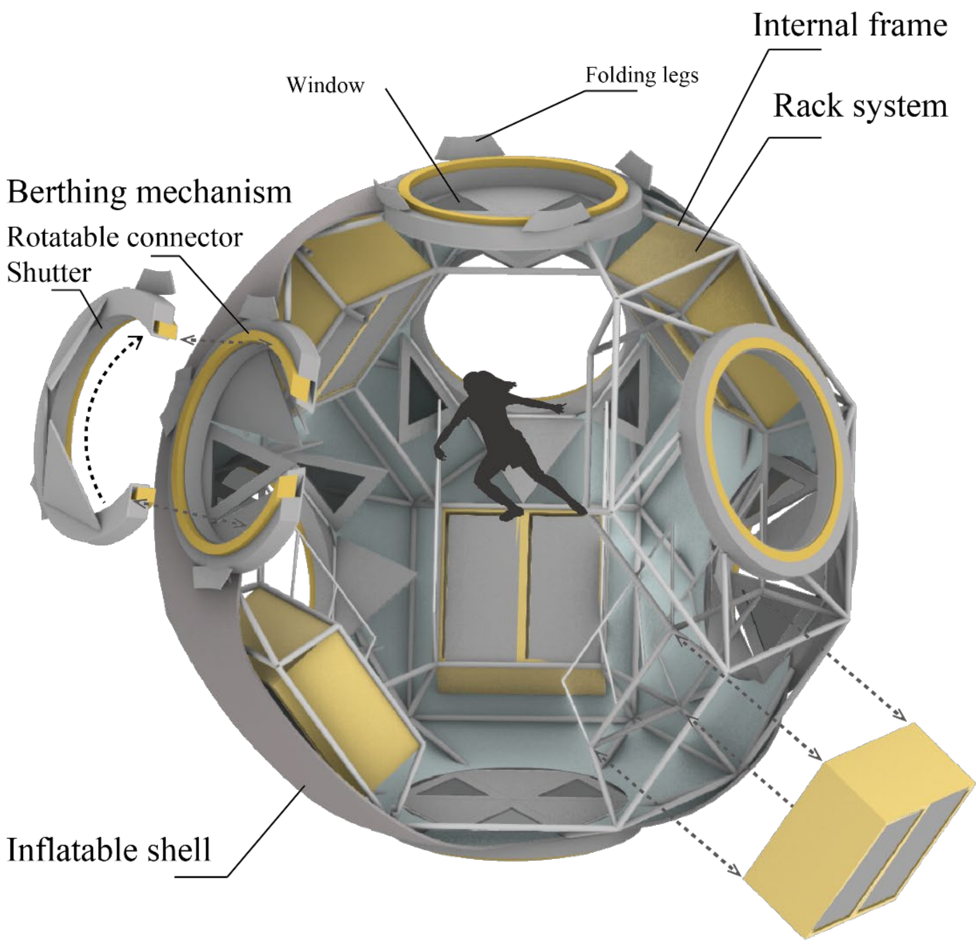


Figure 3. Module 3D view.

The module consists of an inflatable shell. Interior components and utility interfaces are pre-integrated into the module, which can be popped out and used after arrival at the site. The module can also be transported with the components compactly integrated.At launch, the module will remain folded until it is deployed and inflated after arrival at the LZ. The shell is 153 mm thick and is composed of a structural restraint layer (Kevlar), a pressure bladder (polyethylene), and a thermal protection blanket (carbon). [29] Inside the module is a rigid expandable core.The core is made of Bistable Structure, which helps to pre-integrate the interior and components into the module. It is folded at launch and expands in multiple directions upon deployment of the inflatable shell. The rigid expandable core provides structural support for the docking interface even before the inflatable is deployed. The rigid expandable core provides structural support for the docking interface before deployment of the inflatable, secures the racks after deployment, and is capable of withstanding the weight of the crew and the internal pressure of the module. The deployment is shown in Figure 4.

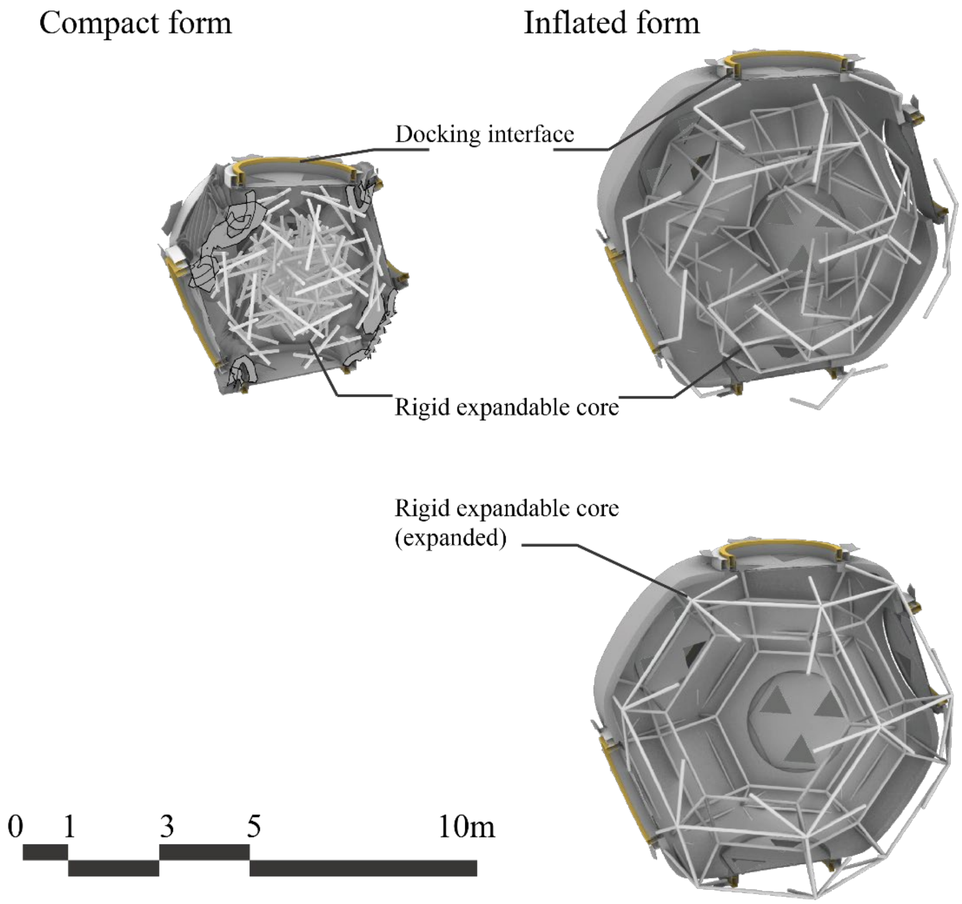


Figure 4. View of inflatable module deployment.

The volume of the modules is 176 m^3. The rack dimensions are (713mm x 853mm x 1552mm) and the volume of each rack is 0.94m^3. The volume of the racks is 0.94m^3 x 12 = 11.28m^3. Each of the 12 racks is assigned to a communication, power supply, and ECLSS. Of the module volume, the effectively used volume is approximately 164.7 m^3. Kennedy et al.[17] require a minimum volume of 70 m^3 per person at the lunar base, which means that each module can accommodate two people. The surface area of the module is 123.8 m^2 and the mass is 4311 kg from Eq. 1. Due to the size of the payload fairing on SpaceX's Starship, four modules can be transported in a single launch, but the mass of the four modules is 17244 kg. Starship can transport 100 tons of mass to the Moon in a single launch, which is a transportable mass.

According to Doule et al.,[25] a minimum of 250 W of power per ton is required to maintain the space station habitat system.Based on this, the power demand to maintain the minimum configuration of four modules would be 4.3 kW, or about 6 kW if comfort and equipment power consumption is included.Since NASA's Kilopower is assumed to provide 10 kW of power,[24] any power that is not sufficient for the batteries on the modules will be supplemented by power from the ground-based Kilopower.

B. Interior Design

Human behavior under lunar gravity differs significantly from that on Earth and in microgravity. The major difference from Earth's gravity is the human locomotion ability, and the difference from microgravity is that the required volume of space is larger due to the absolute direction of gravity and the limitation of vertical movement. First of all, as for the basic posture, when the gravity becomes smaller, the traction of muscles becomes smaller and the body becomes more forward-leaning. In addition, when jumping, they can jump up to a height nearly seven times higher than that of the Earth. Therefore, they would be able to routinely jump over steps of 2 m or more. Also, when walking, the traction force and friction are smaller, so it is difficult to walk as on the earth, and the movement is more like skipping. The average walking speed is about 1.42 m/s[27], although this depends on the method of movement. On the other hand, handrails to aid in movement become more important. In the Apollo 14 movie of astronauts descending from the LM, astronauts can be seen descending a ladder to a height of about 1.5 m above the ground and then moving along the railing of the ladder.[16] The problem with such a jump-based transfer is the risk of hitting one's head on the ceiling. Although the speed and impact of falling are smaller due to the lower gravity, the impact is greater when moving upward. Also, even though it is possible to move up to a height of 2 m with a single jump, the risk of hitting one's head would be higher due to the greater momentum involved in flying high. Therefore, a method was employed to reduce momentum by making small jumps of about 1400 mm in height while grasping the handrail, even when moving to the upper docking interface. The handrail is an important device to ensure safe and smooth movement in the upper and lower directions.

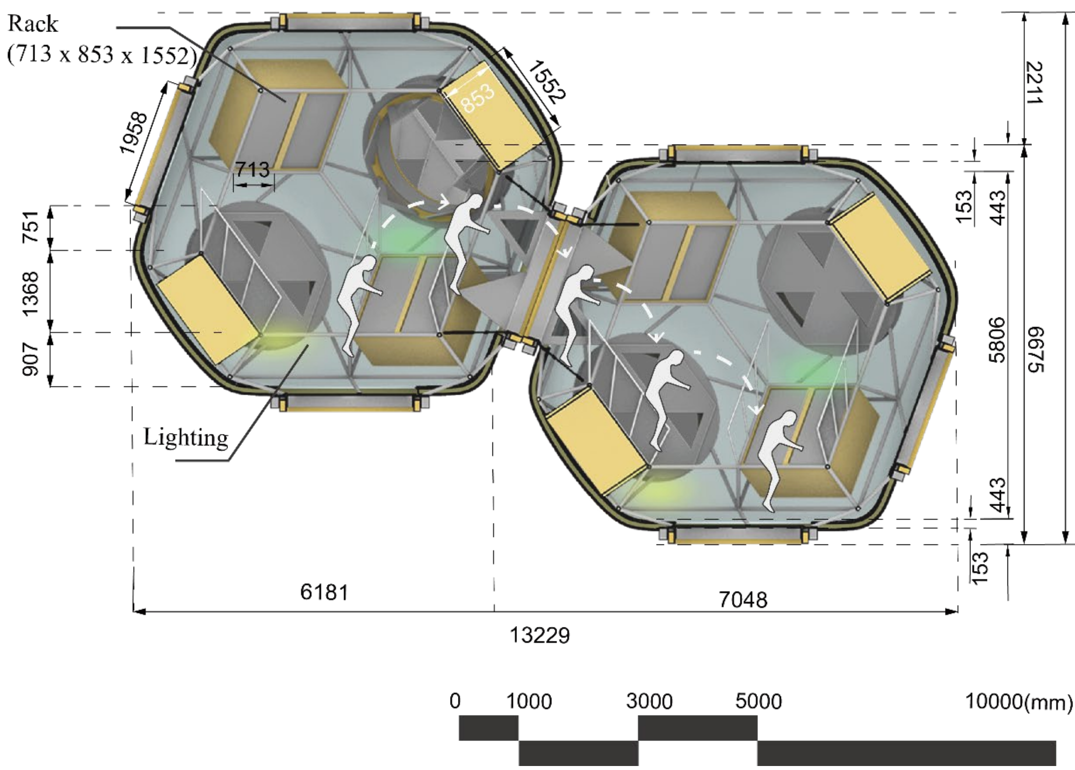


Figure 5. Cross-sectional view and how to move inside pressurized space.

The hexagonal floor shape may make the current location and the orientation of each room less clear than in a cubic room. In addition, each time the module is reconfigured, the use of the room changes. Therefore, Lighting is installed near the docking interface. Each room is identified by the difference in color of this Lighting. In addition, in the event of an emergency evacuation (described below), the module indicates the shortest route to the evacuation module calculated by the module by the color of this lighting. This enables safe evacuation.

Figure 6. Interior View.

C. Construction Method

Lava tubes are underground formations formed by the flow and drainage of lava. Lava tubes have been observed on the Earth, the Moon, and the Moon's surface, and some of the largest tubes are several kilometers in length. [19]Since lava tubes are hollow, the bedrock that serves as the ceiling may collapse under its weight or due to impact by meteorites, or there may be areas where the ceiling was not originally formed, forming holes that connect the lava tube to the surface like skylights. Many of these holes have been observed on the Moon. The size of these holes varies from place to place. For example, the Marius Hill Hole (MHH) confirmed in 2008 was found to be 59 m × 50 m in size and 49 m deep. [20] It has been pointed out that these lava tubes may store water, which is essential for human survival. The ceiling of the lava tube is several tens of meters thick and is expected to protect against radiation and MMOD. Radiation levels on the lunar surface exceed JAXA's suggested lifetime limit of 1.2 Sv for astronauts[23], but it is believed that radiation levels at the bottom of the hole will be reduced to about 10% of those at the surface. In addition, temperatures are stable, with daily temperatures on the lunar surface ranging from -170°C to 110°C, but -20°C to 30°C in the shaded areas at the bottom of the hole, and areas with even lower radiation levels and more stable temperatures may be identified in some locations.[22] On the one hand, some rock formations are collapsing. On the other hand, there is a risk of collapse in some rock formations, and this is an area that has not been well investigated.

Furthermore, a near-vertical hole with a height of several tens of meters requires a construction method that can follow its shape, autonomously explore its interior, and change its configuration. The construction method we are aiming for in this paper is one in which the modules maintain a minimum configuration of four modules, while their rotatable connectors rotate and use each other like wheels, rolling and self-assembling. The aim is to continuously explore the lunar surface and the lava tube, and eventually construct a large base.

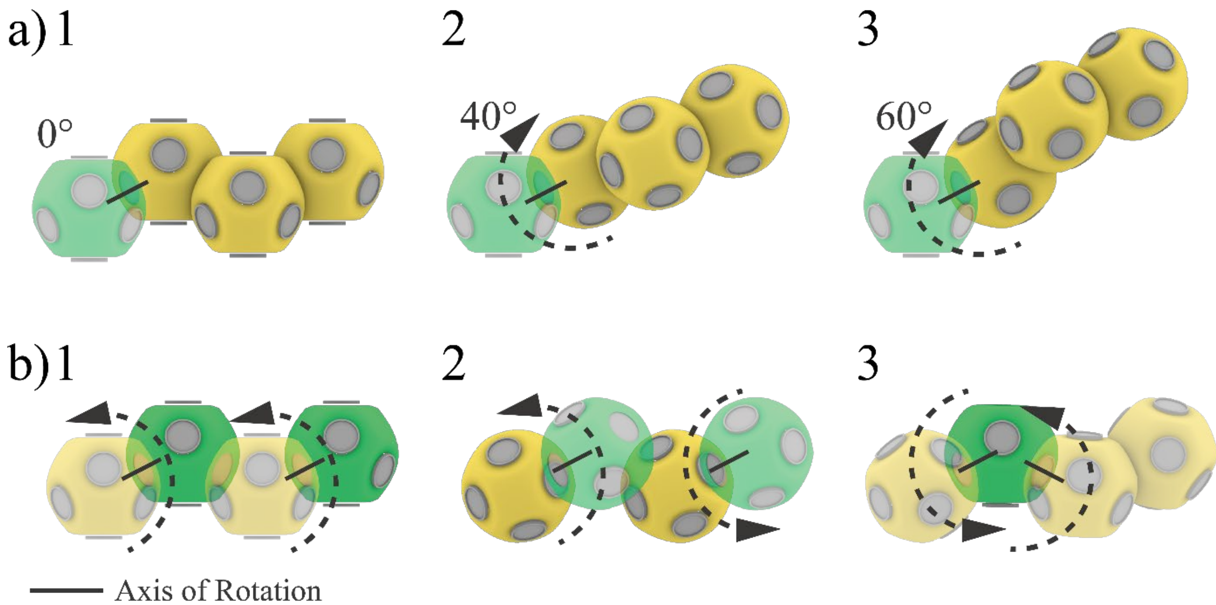


Figure 7. Deformation of module configuration by rotation of rotatable connector.

Figure 7 shows a diagram of the configuration and movement method of the minimum configuration of four modules. The minimum configuration of 4 modules functions as a kind of "Kinematic chain" due to the "easy-to-rotate" module shape of the truncated octahedron and the rotation mechanism of the Rotatable Connector. This operation resembles an industrial robot arm composed of rings and joints, but by changing the direction of connection, disassembly, and repositioning, a chain with a degree of freedom can be configured. By adding modular deformation to the construction system through the rotation of the rotatable connector, it is possible to 1) Complex and highly flexible module configurations can be realized. 2) Geometric changes in the module configuration can be realized. 3) The geometry of the structure can be changed during construction. This allows for complex terrain geometries such as lava tubes and sudden changes in design requirements such as changes in use cases. Specifically, if there is a sudden decision during construction to change the construction site or change the operation plan, the Rotatable connector will autonomously calculate the configuration changes and configuration optimization, which will then be executed by the Rotatable connector to construct the base. As shown in Figure 7, each of the eight Rotatable connectors in each module can rotate in a different direction, and the rotation axis of the module is always changed. Therefore, as the number of modules to be combined increases, the direction of movement by rotation of the rotatable connectors and the shapes that can be configured become more diverse.

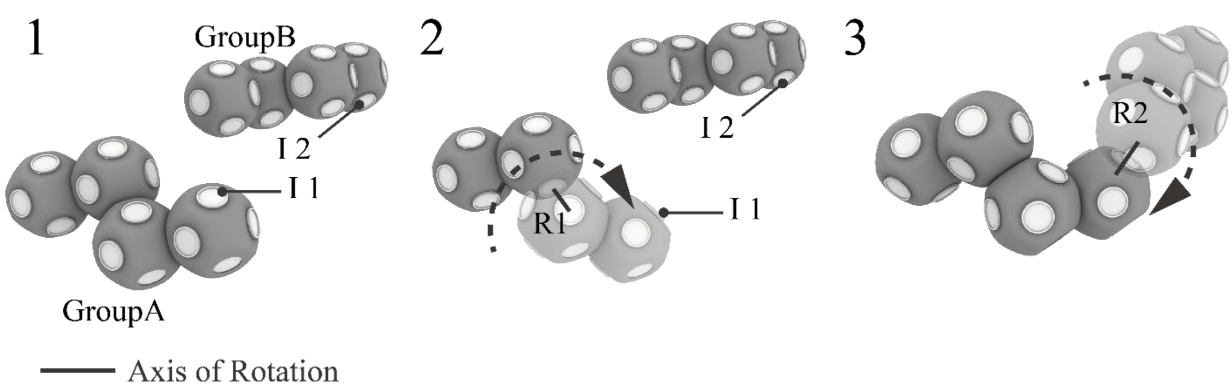


Figure 8. Two minimum configuration modules repeat Deformation and combine.

Figure 8 shows how the minimum configuration of 4 modules is combined to realize an 8-module configuration. In Figure 8.1, Group A and B have a total of 26 dockable interfaces. Here, we calculate the interfaces (I1, I2) that are easiest to dock with each other and the rotatable connectors (R1, R2) that have rotational axes that are easiest to dock with each other. We also calculate the module configuration that can achieve a smaller surface area and a pressurized space for easy movement after configuration with 8 modules. Then, as shown in Figure 8.2, the position of the center of gravity and the distance between each other are calculated, and based on the results, the kinematic chains are deformed. As shown in Figure 8.3, by docking I1 and I2, a total configuration of 8 modules is realized, and after Figure 8.3 is realized, the configuration can be decomposed again or changed to a more optimal configuration depending on the situation. The introduction of a series of construction methods allows seamless exploration of the site, transportation of modules, construction of the base, and modification of the base structure at the lunar base.

V. 100 Modules Swarm Habitat

A. Modular Coodination

In this paper, a Lava tube with a height of 45 m, depth of 550 m, roof thickness of 45.6 m, and a hole of 35.6 m*45 m in size was modeled in Rhinocerous3D as the site. Figure 9 shows the construction of the site. The 100 modules are successively deformed by rotating the rotatable connectors and descending from the edge of the hole to the bottom of the Lava tube. Finally, the lunar base is completed with 100 modules attached to the Lava Tube. Since the modules are connected in their interior space, the crew can move from the basement of the Lava tube to the lunar surface simply by jumping around inside the pressurized space. For architectural functions, the entire Swarm Habitat will be constructed based on a minimum configuration of four modules. The minimum configuration consists of one Private Module (164.7 m^3) with a toilet and bedroom, two Greenhouse Modules (329.4 m^3) with hydroponics facilities, and one Sanitation Module (164.7 m^3) with a kitchen. As the number of residents increases and the work becomes more multifunctional, a Working Module (164.7 m^3) with research facilities and office functions is added. In this paper, the minimum configuration was devised based on JAXA's Report of Lunar Farming Concept Study Working Group[1st[26]], aiming to construct a completely closed environment and to secure at least 70m^3 of private space per person. To construct a fully enclosed loop with plant cultivation, a plant cultivation unit of 103 m^3 per person is required. In the Swarm Habitat, circulation of air, water, and waste is achieved through the combination of the ECLSS of the Rack System and the plant cultivation unit, but if a plant cultivation unit of this size could be installed in the Greenhouse Module, it would be possible to construct a completely closed loop in the base. Figure 9 shows the process of assembling 100 modules. The breakdown of each module in the state of 100 units is as follows: Private Module: 35, Greenhouse Module: 49, Sanitation Module: 9, Working Module: 7. Of this volume, 6917 m^3 is allocated to living rooms, workplaces, and warehouses, and 5163 m^3 to circulation and environmental maintenance (when half (82.35 m^3) of the effective volume of the Agriculture Module is allocated to plant cultivation). If 103m^3 of plant cultivation units could be installed, 78 people could be accommodated. The maximum number of occupants is 98 when the volume of 70 m^3 per person is maintained. When the 100-module configuration and its Deformation are executed, a huge number of "connectable interfaces" and a huge number of rotation directions emerge. It is necessary to search for and execute a configuration that can be changed while maintaining a stable center of gravity position and stable coupling of the pressurized space.

B. Mission Phasing

The process of building a 100-module Lavatube habitat will have four major phases. The modules in this work are designed to fit into the Starship's payload fairing, so the modules will be transported by the Starship, but since the actual transport volume is currently unknown, the initial phase will use Falcon heavy to transport power generation equipment, ECLSS, etc. [28]

Phase 1 (2028-2031) This phase will be devoted mainly to exploration, with Starship launching modules twice a year for a total of 32 modules to move autonomously and explore the habitable Lavatube. In addition, two personnel, power generation equipment, and ECLSS will be transported by Falcon Heavy once a year starting in 2030.

Phase 2 (2032-2035)During these four years, Starship will transport modules three times a year and Falcon heavy twice a year will transport support materials and five personnel.

Phase 3 (2036-2037)During these two years, Starship will transport modules three times a year. By 2036, 100 modules will be in place and settlements of 80 or more people will be built in Lavatube.

It is envisioned that in the nine years of Phase 1-3, the ISS will be able to build a habitat for more than 10 times the number of people on the ISS.

After Phase 4 (2038-), the accommodation area will be further expanded with the retirement of the Falcon Heavy and the Starship's ability to transport 100 personnel.

Advantage of the Swarm Habitat is that it does not need to remain in the same configuration for the entire nine years, as it can move autonomously. As long as a minimum configuration has been established, it is possible to explore the lava tube for several years and join the configuration after the arrival of a new module. Figure 9 is only an example of modular coordination in units of 100 modules, and it is possible to operate different configurations with a smaller number of modules.

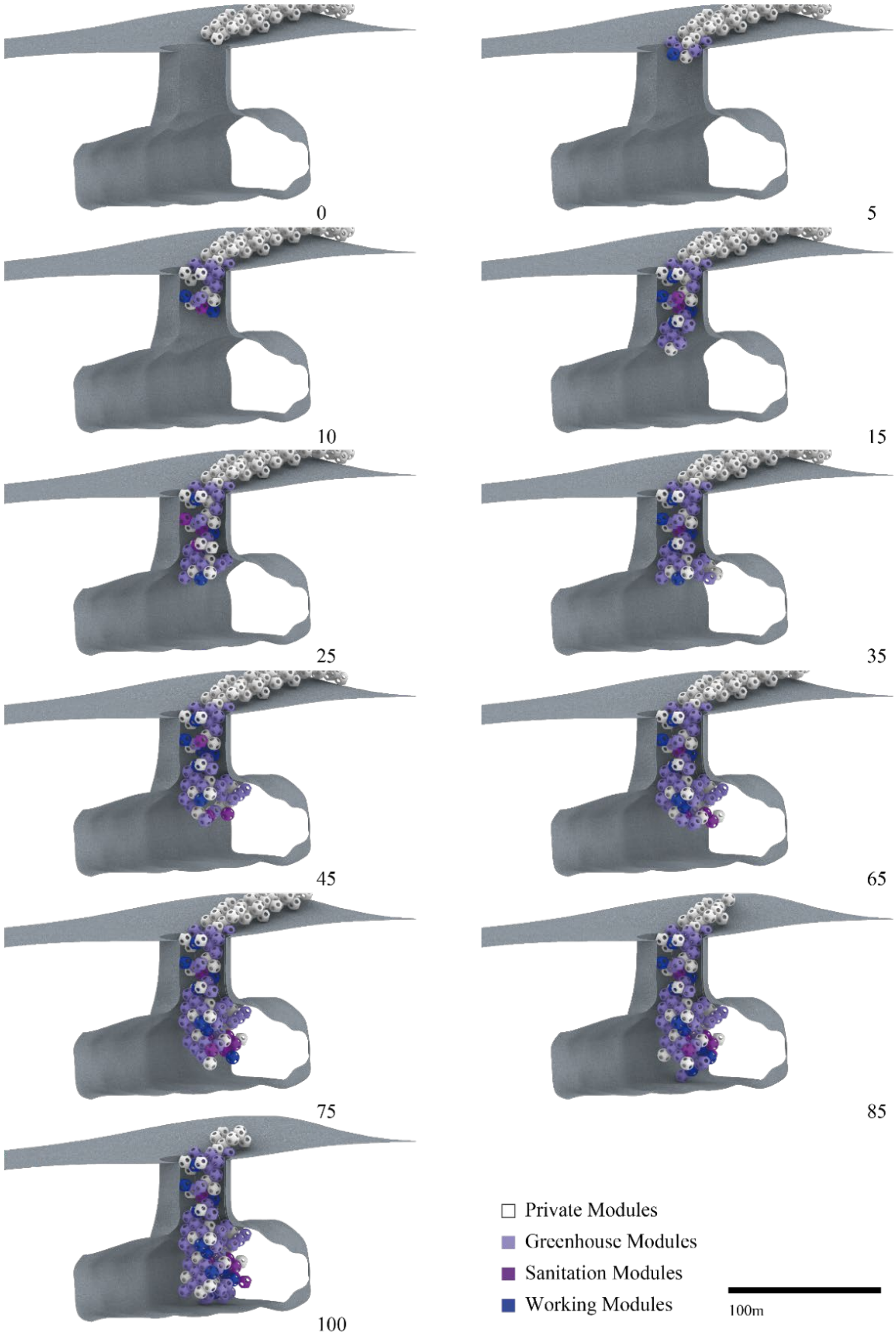


Figure 9. View of module extension.

C. Evacuation Method

In a large lunar base, emergency evacuation must be considered. First, in the case of evacuation from the lava tube itself, the modules on the sides and bottom of the lava tube are designated as Evacuation Modules (Figure 10.1). In case of emergency, the module evacuates to the nearest Evacuation Module from the module it is currently in and waits for help. After the evacuation is completed, the modules are disconnected from each other. In the case of an Evacuation Module attached to the ceiling, the module on the surface will pull it up using cables. For the Evacuation Module at the bottom, the cable is run from the surface to the bottom, and the module at the surface pulls it up in the same manner. Figure 10.3 shows the distance from each module to the Evacuation Module. With the current modular coordination, the maximum time to evacuate to the Evacuation Module is 180 seconds when skipping at a speed of 1.42 m/s. If the Swarm Habitat coupling itself is functioning but the EVA must be evacuated, the spacecraft will skip through the pressurized space and escape to the surface after donning a simple space suit (e.g., Launch Entry Suit). Figure 10.2 shows the translation path of each module. The total distance is 704 meters. Figure 10.4 shows the route from the module closest to the bottom of the Lavatube to the surface. This distance is 477.65 m, which would take 336.37 s (5.6 min) to escape, assuming a skip at 1.42 m/s.

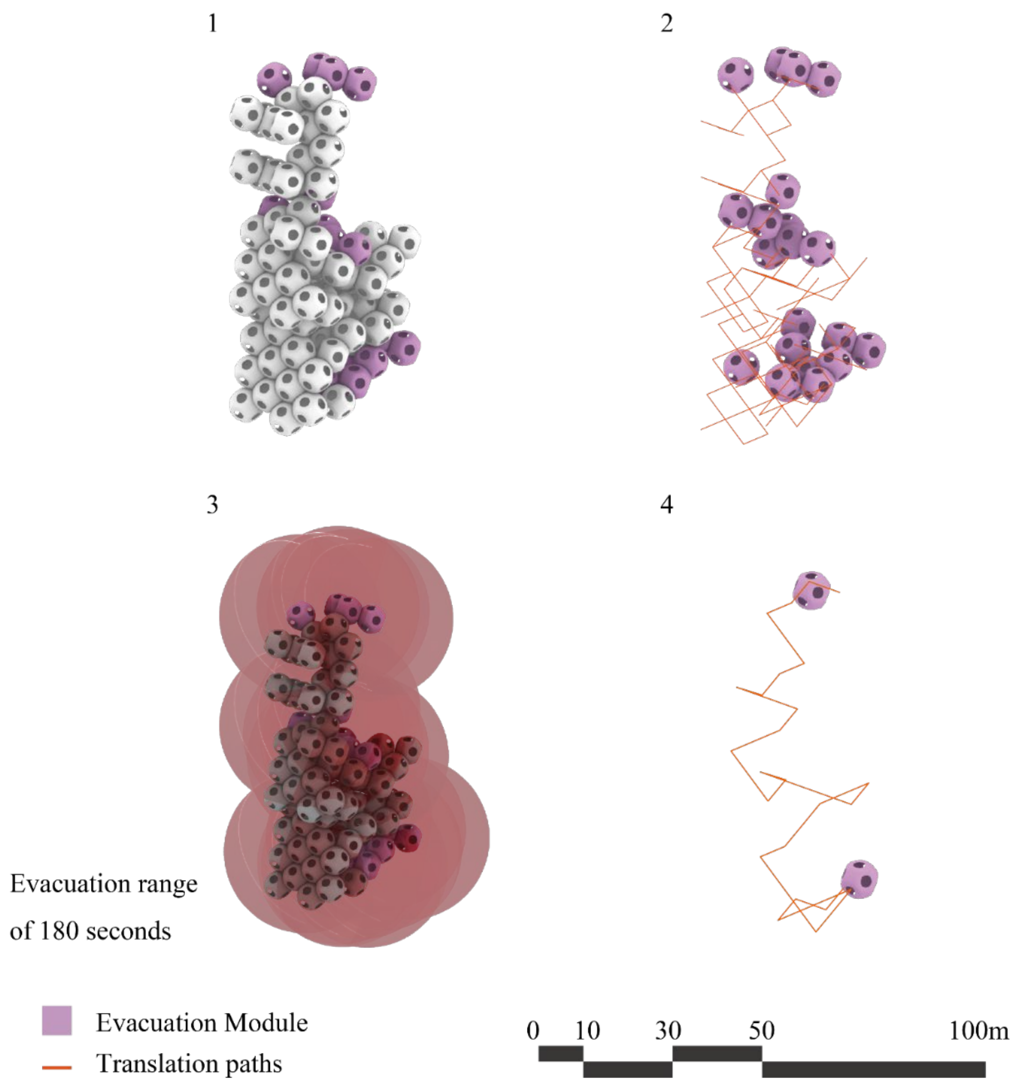


Figure 10. Evacuational translation paths.

VI. Conclusion

Modular coordination consists of the shape and configuration of the modules. In most cases, the pressurized module is cylindrical, indicating that the module is considered and operated like a cube in terms of configuration and interior. In the case of the lava tube, which is considered suitable for establishing a human habitat on the Moon, the topography of the lava tube, with its vertical holes and flat roof, requires modular coordination and architectural design of pressurized space that can be configured three-dimensionally along the topography. The lunar surface is also a special situation in terms of three-dimensional spatial configuration. While under microgravity, one can move unrestrictedly in the vertical direction, on the Moon there is an absolute direction of gravity, albeit smaller than on the Earth. New architectural elements, such as floors and staircases, which are similar to the vertical means of architectural movement on the Earth, but not the same, will be required. Construction methods must also be adapted to the lunar gravity environment.

The method of operating modular structures as Kinematic chains, rather than as simple architectural units, as shown in Swarm Habitat, will allow for the following 1) Site Exploration 2) Transportation of building materials 3) Construction and operation 4) Expansion and configuration changes based on demand The four phases of the project can be done seamlessly. This would reduce the transportation of relief supplies and contribute to the creation of a rational modular coordination system and its long-term operation. Such a concept is also suited to the exploration and construction of large-scale settlements on sites such as the lava tube, where the advantages of habitation have been pointed out, but the interior has not been explored extensively. This is because the autonomous movement of the modules and the degree of freedom of configuration allow for modular coordination with complex geometries.

The realization of the Swarm Habitat is predicated on the integration of expertise from various disciplines, not only space engineering, but also computer science, robotics, and architecture.

1) Analyze a vast amount of information about the terrain conditions, possible rotation angles, internal human vitals and position in pressurized space, expected radiation and MMOD exposure, etc.

2) Evaluate the modular coordination that can accommodate them and their architectural impact.

3)Develop an optimal operation plan.

4) Correct errors accurately based on operational conditions.

It is necessary to establish the above-mentioned flows and design the hardware to realize them. What is presented in this paper is a rudimentary concept for this purpose and a paradigm in the architectural design of a lunar base that could be realized through this process. The next step is to construct more accurately the self-organized movement of the modules in units of 100 using multi-agent simulation techniques. To this end, the research and accumulation in the field of Swarm robotics presented in this paper can provide significant suggestions.

References

[1]"NASA's Plan for Sustained Lunar Exploration and Development." NASA. [Online] Accessed 22 febrary 2023. Available: https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf

[2] " STARSHIP USER`S GUIDE" SpaceX. [Online] Accessed 22 febrary 2023. Available: https://www.spacex.com/media/starship_users_guide_v1.pdf

[3]Howe A. Scott, and Brent Sherwood. (eds.), Out of This World : The New Field of Space Architecture, American Institute of Aeronautics and Astronautics , AIAA, New York, 2000, pp. 7-9.

[4]T.Moriyama and V.Riabov, M.Migita., "The Ability to Express Multiple-Choice Behavior in Pill Bugs," Cognitive Studies: Bulletin of the Japanese Cognitive Science Society, Volume 12 Issue 3 , Sep. 2005, pp., 188-206.

[5]G.Kitmacher and I.Sorokin., "Lessons from the Space Stations for the Future of Space Flight," 70thInternational Astronautical Congress(IAC), Washington D.C.,USA, 21-25 Oct2019

[6]S.Meusburger and O.Bannova., "Reflections on early lunar base design – From sketch to the first moon landing" Acta Astronautica,Vol.202, Jan 2023, pp., 729-741

[7]O.Bannova.," Design Considerations for Exterior and Interior Configurations of Surface Habitat Modules " Journal of the British Interplanetary Society,Vol.60,Sep 2007,pp331-338

[8]M.Yashar et al., "Project Olympus: Off-World Additive Construction for Lunar Surface Infrastructure" 50th International Conference on Environmental Systems, 12- 15 Jul 2021

[9]D.Inocente et al., "Master Planning and Space Architecture for a Moon Village," 70th International Astronautical Congress (IAC), Washington, DC 21-25 Oct 2019

[10]Marc M. Cohen., "Mobile Lunar and Planetary Bases" AIAA 2003-6280, 23 - 25 Sep 2003, Long Beach, California

[11]Yuxiao Tu,Guanqi Liang and Tin Lun Lam.," FreeSN: A Freeform Strut-node Structured Modular Self-reconfigurable Robot - Design and Implementa" IEEE International Conference on Robotics and Automation (ICRA), Philadelphia, USA, May 23-27, 2022. ICRA 2022

[12]Ekblaw A et al.," Space Habitat Reconfigurability: TESSERAE platform for self-aware assembly", 70thInternational Astronautical Congress(IAC),Washington D.C., United States, 21-25 Oct 2019

[13]O.L. de Weck, O. L., Nadir, W. D., Wong, J. G., Bounova, G., and Coffee, T. M., "Modular Structures for Manned Space Exploration:The Truncated Octahedron as a Building Block,"AIAA 1st Space Exploration Conference: Continuing the Voyage of Discovery,AIAA, Orlando, Florida, USA,Feb 2005

[14]Dr. David L. Akin.," Spacecraft Habitability (part 1)" ENAE 697 - Space Human Factors and Life Support, U N I V E R S I T Y O F MARYLAND, State of Maryland,USA,Feb 2023

[15]Wadell, Hakon.," Volume, Shape, and Roundness of Quartz Particles" The Journal of Geology, vol. 43, issue 3,pp.250-280, May 1935

[16] " Apollo14 Video Index." Apollo Flight Journal. [Online] Accessed 22 febrary 2023. Available: https://history.nasa.gov/afj/ap14fj/a14-videoindex.html

[17]Knnedy K, Troups L,Smitherman D., "Lunar Habitation Strategies" AIAA SPACE 2007 Conference & Exposition,Sep 2007

[18]McKeown, K., Dill, H., and Davis, W., "Standard Interface Rack Hardware for Space Station" SAE Technical Paper 951599, Jul 1995

[19]F. Sauro, R. Pozzobon, M. Massironi, P. De Berardinis, T. Santagata, J. De Waele, "Lava tubes on Earth, Moon and Mars: A review on their size and morphology revealed by comparative planetology", Earth-Science Reviews 209 ,2020

[20]Greeley, R.," Lava tubes and channels in the lunar Marius Hills" Moon 1971, 3, pp289–314,Dec 1971

[21]Haruyama, J et al.," Lunar Holes and Lava tubes as Resources for Lunar Science and Exploration",MOON,Springer Link,pp139-161,Jan 2012

[22]Raymond P. Martin and Haym Benaroya.," Pressurized lunar lava tubes for habitation" Acta Astronautica,Vol.204,Mar 2023,pp157-174

[23]Himangshu Kalita and Jekan Thangavelautham.," Strategies for Deploying a Sensor Network to Explore Planetary Lava tubes", Sensors 21(18),Sep 2021

[24]"Kilopower." NASA. [Online] Accessed 09 April 2023. Available: https://www.nasa.gov/directorates/spacetech/kilopower

[25]Ondˇrej Doulea,n, VratislavˇSa´leny´b, Benoˆıt He´rinc, Toma´ˇs Rousek.," Omicron space habitat—research stage II", Acta Astronautica,Vol.70, Jun 2012, pp., 139-153

[26]Lunar Farming Concept Study Working Group.," Report of Lunar Farming Concept Study Working Group 1st", JAXA-SP-19-001,June,2019

[27]D. Hewes, W. Letko, A. A. Spadyk.," The problems of man's adaptation to the lunar environment", NASA,1966

[28]"FALCON USER`S GUIDE" SpaceX. [Online] Accessed 14 May 2023. Available: https://www.spacex.com/media/falcon-users-guide-2021-09.pdf

[29]Kriss J. Kennedy, Constance M. Adams.," ISS TransHab: An Inflatable Habitat",Jan 2000