2025 IEEE/SICE International Symposium on System Integration (SII)
January 21-24, 2025, Munich, Germany

Space-Filling Truncated Octahedron Climbing Modular Robots for the Construction of High-Rise Structures on the Lunar Surface*

Haruho MITSUNAGA[1] and Akio NODA[1]

Abstract—
On the lunar surface, modular robots that can perform multiple tasks through coupling, decoupling, and reconfiguration are expected to play a significant role due to considerations of cost, work efficiency, and fault tolerance. One of the tasks on the lunar surface is the construction of high-rise solar power towers to secure power sources. This study proposes a construction method using modular robots to build high-rise structures on the lunar surface. The shape of both the robots and the structural modules is designed as truncated octahedrons, and four prototypes of these modules have been developed in this study. Additionally, we have previously proposed a method for determining the configuration, position, and posture of modules by discretizing space into truncated octahedron shapes, focusing on their space-filling properties. In this paper, we propose a construction method for building high-rise structures using both the previously prototyped modules and newly propose modules. Significant points of these proposing concept is based on discretizing the workspace using three-dimensional shapes and implements methods of an automated system for the desired task, which can be said that the proposed methods form an efficient and coherent system integration platform on the target missions.

I. INTRODUCTION

One of the robots expected to be utilized on the lunar surface is the modular robot [1][2][3][4][5][6]. Modular robots, capable of performing multiple tasks through coupling, decoupling, and reconfiguration, are attracting attention for their cost-effectiveness, operational efficiency, and fault tolerance. Additionally, one of the tasks required on the lunar surface is the construction of solar power systems. Due to environmental specificities on the lunar surface, tower-type vertical solar arrays are required [7]. Therefore, this research focuses on a method for constructing tall structures, such as vertical solar arrays, on the lunar surface using modular robots. Since modularization is required for the robots, this research also considers the modularization of structure, simultaneously. One construction method that utilizes modules is called modular construction, where pre-standardized modules of structures are manufactured off-site and assembled on-site. In the field of modular construction, research has been conducted on applying space-filling polyhedra to architectural design, showing the potential of using space-filling polyhedral modules for construction. Previous studies on installing and constructing structures using modules include the following. M-blocks [8] stack modules by climbing up the cube-shaped modules. Since there is no distinction between robots and structures, transformation is easily achievable. However, as a structure, it has an excessive number of actuators, and as a robot, it has low operational efficiency. Abdel-Rahman et al. [9] proposed a modular robot that assembles modules in the shape of cuboctahedrons. The structure has no actuators and is effective for constructing large-scale structures, but the robot and structure are non-homogeneous in shape, resulting in limited coupling patterns due to multiple types of modules.

In contrast, this study aims to improve both operating efficiency and coupling patterns of multiple modules by homogenizing their geometry. This paper proposes a construction method that leverages the homogenized shapes of various modules. And, this research utilizes space-filling polyhedra as the shape of modules for both of the structures and robots. In previous studies, we introduced parallel polyhedra, which can fill space solely through translation, and had proposed a method to modularize robots and structures in the shape of a truncated octahedron [10][11]. Additionally, we had proposed a method that leverages the space-filling properties of the modules to geometrically determine the configuration and positions of the modules without the need for complex calculations [11]. Now, this paper proposes a new construction method using truncated octahedron modules and discusses the necessary modules and configurations to realize this method. The newly proposed module for realizing the construction method presented here reduces the number of modules required for the construction process compared to conventional approaches. This contributes to weight reduction and a decrease in the torque required by the robot. Furthermore, we will verify the effectiveness of the proposed method by applying the previously proposed method for determining module configurations to the construction method described in this paper.

Significant points of the proposing concept is based on discretizing the workspace using three-dimensional shapes called truncated octahedrons, and both the robots and the structural modules is designed as concatenation of those shapes. For the reasons discussed below, the proposing methods embody methods of implementing an automated system for the desired task, which can be said that the proposing methods form an efficient and coherent system integration platform.

II. PROPOSED METHOD

We propose a method for constructing high-rise structures using multiple types of modules with different functions

---

*This work was supported by JST Moonshot R&D Program, Grant Number JPMJMS223B.

[1] Haruho Mitsunaga and Akio Noda are with Faculty of Robotics & Design, Osaka Institute of Technology, 1-45 Chayamachi, Kita-ku, Osaka City, Osaka

979-8-3315-3161-4/25/$31.00 ©2025 IEEE

standardized to a uniform shape of a truncated octahedron. At first in this section, we discuss the modules previously prototyped by the authors, the methods for determining the configurations and postures for combining these modules, and then the construction method proposed in this paper.

A. Shape of the module

This section introduces the modules previously prototyped by the authors, which are used in the construction method proposed in this paper. To standardize the shape of both the robot and the structural modules, the authors selected a shape that emphasizes connectivity as a robot and rigidity as a structure. In the modules prototyped by the authors [10][11], the shape of the modules focused on space-filling polyhedra, using truncated octahedrons. A space-filling polyhedron is a polyhedron that can fill space without gaps, and among them, polyhedra that can fill space only by translation are called Parallelohedra. It has been proven by E.S. Fedorov that there are only five types of parallelohedra: the cube, truncated octahedron, hexagonal prism, elongated rhombohedron, and rhombic dodecahedron [12]. In this study, we adopted the truncated octahedron after comparing the following four aspects of the parallelohedra: mirror symmetry of the coupling faces, the number of axes of symmetry of the coupling faces, the number of coupling faces, and the angles between the coupling faces.

We will now describe the four types of modules prototyped so far. These are primarily based on the shape of a truncated octahedron, with the coupling faces designed to be easily connected by press-fitting magnets.

The Basic-module (Fig.1) serves as the fundamental module and does not have any actuators, primarily functioning as the link parts of the robot.

The joint-module (Fig.2) consists of two coupling faces and a single servo motor. Its range of motion is defined as $-109.5 \leq \theta \leq 109.5$ degrees, with the upright position where the two coupling faces are parallel being considered 0 degrees. When $\theta = -70.5, 0, 109.5$ degrees, the joint-module forms two of the eight regular hexagonal faces of the truncated octahedron, matching the shape of a part of the truncated octahedron.

The EE (End-Effector)-module (Fig.3) comprises one coupling face, a servo motor, and a three-finger gripper. This module can connect to structural modules without actuators. The three-finger gripper opens by rotation and grips the hexagonal face of the structural module from the inside to establish a connection. Since the distance from the coupling face to the gripping position is the same as the distance between opposite faces of the truncated octahedron, it matches the shape of a part of the truncated octahedron.

The structure-module (Fig.4) is a module intended to become a part of the structure rather than function as a robot. It is a module with added connector parts that absorb assembly errors, added above and below the square faces of the Basic-module to facilitate easy assembly.

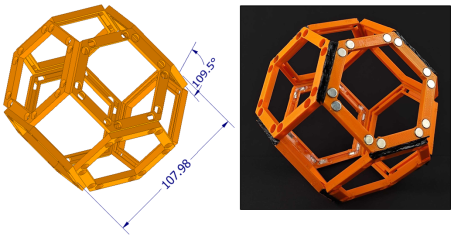

Fig. 1. Basic-module

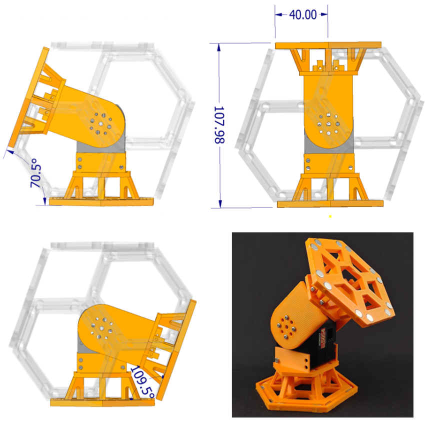

Fig. 2. Joint-module (takes the shape of a truncated octahedron when at angles $-70.5, 0, 109.5[degrees]$)

B. Methods for determining module configuration and orientation using space-filling properties

We describe the method for determining the configuration and posture of truncated octahedron modules, as discussed in the previous section, focusing on the space-filling properties of the modules previously proposed by the authors [11]. All robots proposed in this study are standardized to the shape of a truncated octahedron. Therefore, as shown in Fig.5, the space is discretized into truncated octahedrons, and the position of each module is selected from within this space. By determining the position and posture of the modules to be coupled from the space-filled truncated octahedrons, the coordinates of the target position and the angles to the target posture can be geometrically determined without requiring complex calculations. In this paper, we will refer to this method as the module configuration determination method.

To verify the effectiveness of the proposed method, the configuration and posture of the modules were determined using this method, and their operation was performed. As a

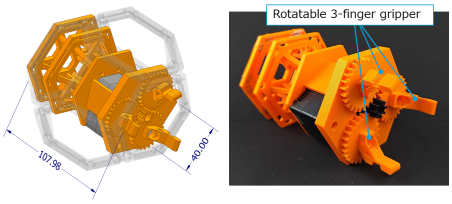

Fig. 3. EE(End-Effector)-module

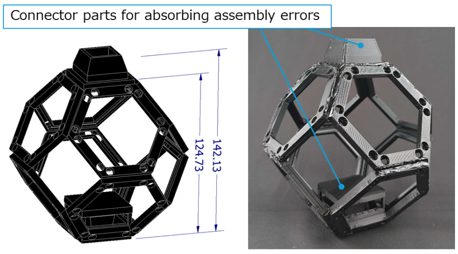

Fig. 4. structure-module

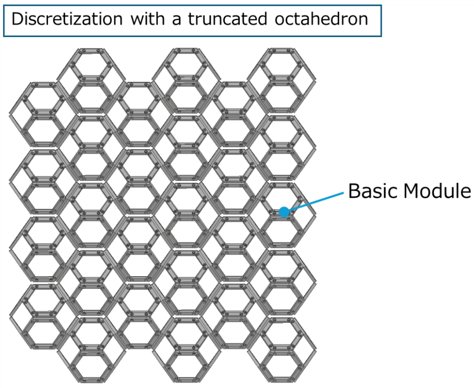

Fig. 5. The discretization of space using truncated octahedrons (Basic-Module).

benchmark test for the operation, we checked whether the robot, with the modules coupled, could climb a single layer of pre-installed structure modules. As shown in Fig.6, the coupling configuration, initial posture, intermediate posture, and target posture of the modules were determined from the discretized space of truncated octahedrons, and it was confirmed that the desired operation could be performed by moving the joint modules to the geometrically determined target angles. This demonstrates the effectiveness of this method.

C. *Construction method using modular-climbing-robot*

This section describes the construction method proposed using the modules, their configurations, and the posture determination methods discussed in the previous sections. All modules used in this study are standardized to the same shape of a truncated octahedron. Specifically, the only difference between the structure module and the Basic module is the addition of parts for coupling. Therefore, the structure module can be used as part of the robot in the same way as the Basic module. Thus in this paper, we propose a construction method that treats the structure module both as a part of the robot and as a structure itself.

First, the structure module is combined with the robot's modules, similar to an inchworm. This robot climbs up the already installed structure modules. Upon reaching the highest point, it assumes a posture that straddles the already installed structure modules. Subsequently, the structure module, which was previously part of the robot, is attached to the already installed structure modules and then separated from the robot. The robot, now separated from the structure module, divides into two parts, each descending separately. The conceptual diagram of this proposed method is shown in Fig.7.

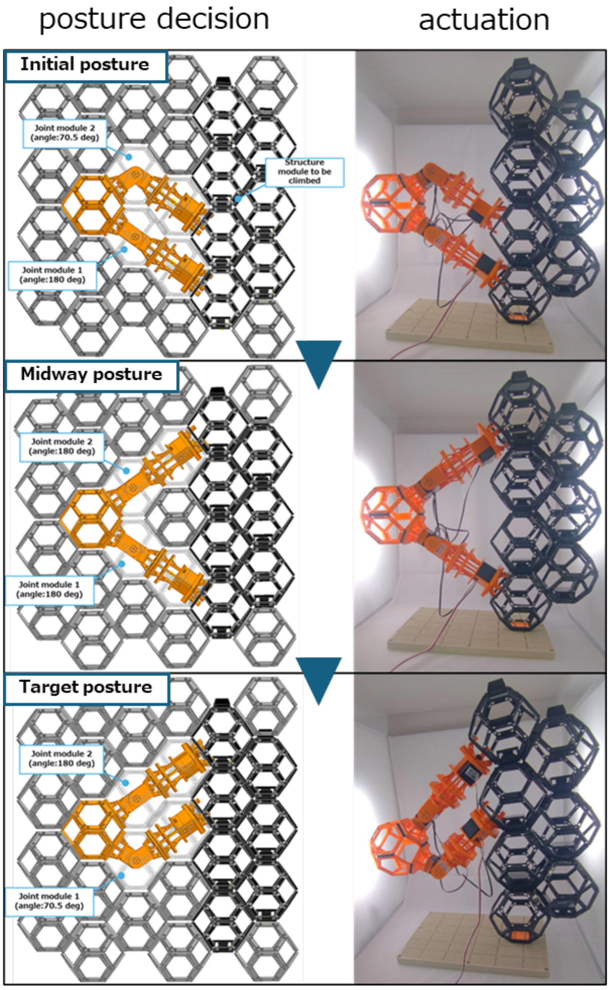

Fig. 6. Module configuration and position/posture determination method (Left: Determination of module configuration and position/posture within a space discretized into truncated octahedrons; Right: Actual operation of combined prototyped modules).

III. COMPOSITION OF THE MODULES OF THE PROPOSED CONSTRUCTION METHOD

To realize the operation shown in Fig.7, the configuration of the modules is determined using the the module configuration determination method proposed in this study. The construction method proposed here employs the structure-module as part of the robot. Since the structure-module lacks coupling faces, it requires connection through gripping with the EE (End-Effector). Therefore, in this paper, we propose a new EE-joint-module to achieve this.

A. *EE-joint-module*

In this paper, we propose a new EE (End-Effector) -joint-module, which is a joint-module designed for connecting with the structure-module. Since the structure-module does

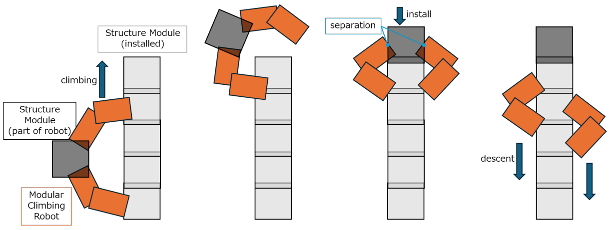

Fig. 7. Construction methods that use structural modules as both robots and structures

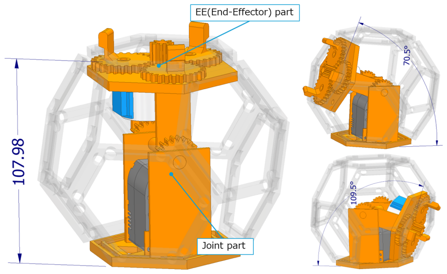

Fig. 8. EE(End-Effector)-joint-module

not have coupling faces with press-fitted magnets, it connects through gripping with the EE. Therefore, we designed the EE-joint-module by replacing one of the two coupling faces of the joint-module with an EE-part. This is shown in Fig.8. By using this module, it is possible to connect to the structure-module while retaining the functionality of the joint-module. In other words, where traditionally both an EE-module and a joint-module have been required, the EE-joint-module can replace them with a single module. As shown in table I, this allows a reduction of 88 [g] in mass and 107.98 [mm] in length per EE-joint- module compared to the conventional approach. In the proposed construction method, the robot works against the direction of gravity, making the weight reduction effective. In addition, the reduction in length after joining the modules is beneficial as it reduces the torque during operation.

B. *Consideration of initial posture*

In this section, we examine the initial posture for the proposed construction method using the module configuration determination method. It has been demonstrated that a 3-degree-of-freedom serial link combined with a Z-axis rotation mechanism can climb three-dimensional structures with bends and branches, such as pole-shaped structures [13]. Since the objective in this study is not to climb structures with bends or branches, we will implement a serial link configuration. In our proposal, the structure-module is used as part of the robot during climbing and is separated after assembly to descend as two individual robots. Therefore, the condition is that both ends of the structure-module must connect to a 3-degree-of-freedom serial link to allow for descent. First, we consider the initial posture similar to that in Fig.6 using the newly designed EE-joint-module. As shown in Fig.9, the orientation of the coupling part of the structure-module differs from that of the already installed ones, requiring additional degrees of freedom to rotate this orientation during assembly. Since lightweight design is crucial for climbing operations, increasing the degrees of freedom would lead to an increase in weight, making it unsuitable. Therefore, as shown in Fig.10, the optimal initial posture is one in which the orientation of the structure-module aligns with that of the already installed modules.

TABLE I

COMPARISON OF CONVENTIONAL AND EE-JOINT-MODULE

	mass [g] (Measured value)	length [mm] (Design value)
EE-module + jonit module	161 +153	107.98 + 107.98
EE-joint-module	226	107.98
difference	88 (72.0%)	107.98 (50.00%)

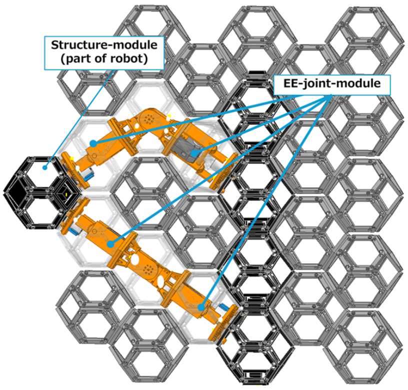

Fig. 9. Candidate configuration of modules for the proposed construction method1 (unsuitable due to the different orientation of the joints of the structure modules)

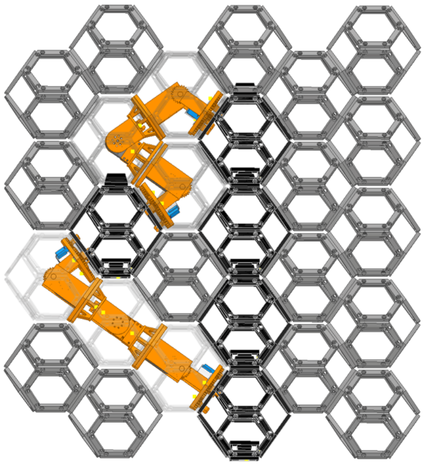

Fig. 10. Candidate configuration of modules of the proposed construction method1 (appropriate orientation of the joints of the structure modules)

IV. RESULTS OF APPLYING THE MODULE COMPOSITION METHOD

Fig. 11 shows the posture transitions of the modules determined by applying the module configuration method

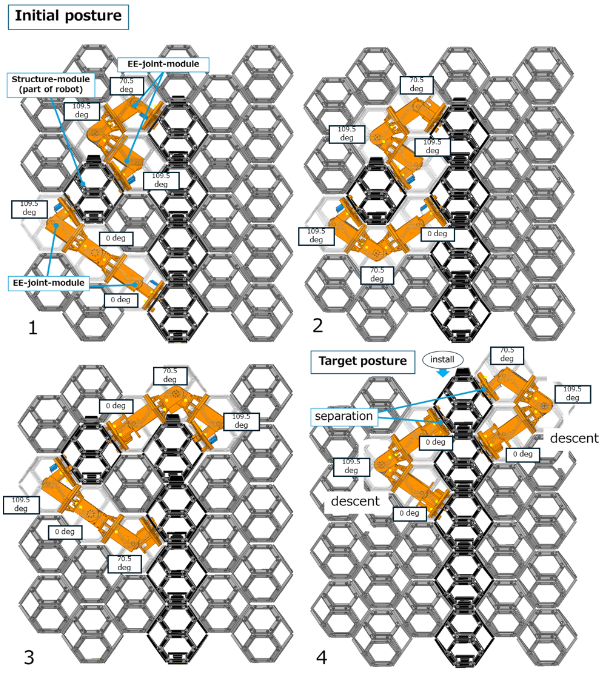

Fig. 11. Diagram of the module transitions of the proposed construction method using the module composition decision method

from the initial posture decided in the previous section. As shown in the figure, by using the newly developed EE-joint-module and applying the module configuration method proposed in this study, the target positions and target angles for the robot's motion transitions in the construction method proposed in this paper were geometrically determined. Furthermore, as described in Section III.B, the EE-joint-module allows for a reduction of 88 [g] in mass and 107.98 [mm] in length per module compared to conventional modules. That is 72.0% and 50.00% of the total amount,respectively. As can be seen from the figure, this module configuration uses four EE-joint modules. In other words, in the proposed configuration, the EE-joint modules achieved a total reduction of 352 [g] in mass and 431.92 [mm] in the overall robot length when connected in a straight line.

V. DISCUSSION

As a results, the target positions and target angles for each module necessary to realize the construction method proposed in this paper were obtained. Therefore, it is considered that by fabricating the newly designed EE-joint-module and assembling it with the previously created modules according to the determined configuration, and operating them to the target angles, the intended operation can be realized. Moreover, the configuration, positions, and orientations of the modules required to achieve the intended operation were determined geometrically without the need for complex calculations. This demonstrates the effectiveness of the proposed module configuration determination method utilizing the space-filling property of the truncated octahedron.

In addition, when the number of modules in the structure is n, the number of couplings $f(n)$ and the total angle $g(n)$ are, respectively, as follows

$$\sum f(n) = 5n - 11 (4 \leq n)$$

$$\sum g(n) = 1002n - 1441.5 [deg] (4 \leq n)$$

The increase in both the number of couplings and the total amount of angles as n increases can be seen to be $O(n)$, using Landau's notation. Of course, there are obstacle avoidance movements and acceleration/deceleration control of each axis is necessary, which means that this should be verified by actual machine experiments.

VI. CONCLUSIONS

In this paper, we proposed a construction method for building high-rise structures on the lunar surface using a truncated octahedron module-type climbing robot, which we have previously proposed. Furthermore, we proposed new modules that were deemed necessary based on the proposed construction method. With the proposal of the new module, it has become possible to achieve a configuration that is lighter and has a shorter overall robot length compared to using only conventional modules. To verify the feasibility of the proposed construction method using these modules, we applied the previously proposed module configuration and position/orientation determination method that utilizes the space-filling property of the truncated octahedron. As a result, we obtained the target angles for each module, suggesting that the proposed method is feasible.

Now, starting from the discretization of the workspace using three-dimensional shapes called truncated octahedrons, both robots and structural modules were designed as a conjunction of those shapes, joint angles at working position could be also determined naturally. In the end, the described set of methods embodies a way to implement an automated system for a desired task, and the proposed method forms an efficient and coherent system integration platform.

As for future prospects, it is necessary to fabricate the newly designed modules and conduct actual verification by assembling and operating them in the configuration determined in this paper. Additionally, while this study examined the postures from climbing to assembly and descent, it is believed that by enabling attachment maneuvers and reassembly movements of the modules after descent, the proposed operation can be repeated, making actual construction possible. Currently, the focus is on the mechanism of the construction method for use on the lunar surface. Looking further into future prospects, future developments will need to consider operating these systems on the actual lunar surface. This will require hardware improvements to withstand the lunar environment, such as dust resistance and durability against temperature fluctuations.

ACKNOWLEDGMENT

This work was supported by JST Moonshot R&D Program, Grant Number JPMJMS223B.

REFERENCES

[1] Haruhisa Kurokawa et al., ”Modular Robot: Self-Reconfigurable and Mobile Modular Robot (M-TRAN),” Journal of the Robotics Society of Japan, vol. 21, no. 8, pp. 855-859, 2003.

[2] LORDOS, George C., et al: WORMS: A Reconfigurable Robotic Mobility System for Extreme Lunar Terrain; ASCEND 2022, p.4395 (2022)

[3] TU Yuxiao, LIANG Guanqi, and LAM Tin Lun: FreeSN: A Freeform Strut-node Structured Modular Self-reconfigurable Robot-Design and Implementation; 2022 International Conference on Robotics and Automation (ICRA), IEEE, p. 4239-4245 (2022)

[4] KALOUCHE Simon, ROLLINSON David, and CHOSET Howie: Modularity for maximum mobility and manipulation; Control of a reconfigurable legged robot with series-elastic actuators: 2015 IEEE international symposium on safety, security, and rescue robotics (SSRR), IEEE, p.1-8 (2015)

[5] Gerbl, Michael, et al: PARTS—A 2D Self-Reconfigurable Programmable Mechanical Structure; Robotics 13.5 , 77 (2024)

[6] BRANDT David, CHRISTENSEN David Johan, and LUND Henrik Hautop: ATRON robots: versatility from self-reconfigurable modules; 2007 international conference on mechatronics and automation, IEEE, p.26-32 (2007)

[7] Mitsubishi Research Institute, Japan Space Forum: ”Report on the 2021 Space Development and Utilization Promotion Research and Development (Development of Energy-Related Technologies on the Moon (Technical Issues Organization)),” Report, 2022. Accessed on October 24, 2023. `https://www.meti.go.jp/meti_lib/report/2021FY/000341.pdf`

[8] John W Romanishin, Kyle Gilpin, and Daniela Rus: M-blocks: Momentum-driven, magnetic modular robots; 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 4288 – 4295, (2013)

[9] Amira Abdel-Rahman, Christopher Cameron, Benjamin Jenett, Miana Smith, and Neil Gershenfeld: Self-replicating hierarchical modular robotic swarms; Communications Engineering, Vol. 1, No. 1, p. 35 (2022)

[10] Haruho Mitsunaga and Akio Noda, ”A Proposal of Construction Method of High-Rise Structures on the Moon Using Modular Climbing Robots,” Proceedings of the 24th Symposium on System Integration of the Society of Instrument and Control Engineers, pp. 1445-1447, 2023.

[11] Mitsunaga Haruho and Akio Noda, ” Modular Climbing Robot Using the Truncated Octahedron
for Construction of High-Rise Structures,” Proceedings of the Annual Conference of the Institute of Systems, Control and Information Engineers, Kyoto: Society of Instrument and Control Engineers, May 2024, 68, 836-839. Available at: https://cir.nii.ac.jp/crid/1520019125726503808.

[12] Marjorie Senechal and R. V. Galiulin: “An Introduction to the Theory of Figures: the geometry of E.S. Fedorov” .1984. url: https : / / api . semanticscholar. org / CorpusID :118440872

[13] Mahmoud Tavakoli, Ali Marjovi, Lino Marques, and Anibal T de Almeida: 3dclimber: A climbing robot for inspection of 3d human made structures; 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 4130 – 4135 (2008).