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Second report on Space-Filling Truncated Octahedron Climbing Modular Robots for the Construction of High-Rise Structures on the Lunar Surface: Experimental Validation of Assembly Motion*

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Abstract— **In recent years, with the rapid advancement of space development, there has been increasing demand for constructing solar power generation systems on the Moon using modular robots. This study has been proposing a modular construction method aimed at building tall structures on the lunar surface. Their modules adopt a truncated octahedron shape one of a space-filling polyhedron allowing their configuration and placement to be determined geometrically by exploiting its space-filling property. This approach can also be treated as a space quantization and establishes a unified platform in which module development, configuration, and positioning can be derived with comparatively simple calculations. In this paper, we present the results of a field experiment using newly prototyped modules, along with the previously proposed construction method and module design. The results demonstrate the feasibility of the proposed method and highlight the potential for space quantization for robot motions based on space-filling properties.**

I. INTRODUCTION

In recent years, with the boom in space development, modular robots [1] [2] [3] [4] have been expected to play a significant role in terms of cost, workability, and fault tolerance. These robots can change their shape by combining and separating modules, enabling a single unit to perform multiple tasks. Additionally, due to their structural design, modular robots can be reconfigured into various shapes, allowing for flexible adaptation to diverse terrain and environmental conditions. Furthermore, in the space environment, modularization has also been closely examined for applications beyond robotics. For example, Mizuguchi et al. [5] proposed modularizing living modules into polyhedrons, while de Weck et al. [6] demonstrated that using space-filling polyhedron modules in manned spacecraft offers advantages in reusability and launch packing efficiency.

In this study, we aim to construct a high-rise solar power array [7] for deployment on the lunar surface. To achieve this, we propose a construction method in which both robots and structures share a unified modular shape. This module-based approach reduces on-site workload and is well suited to construction in harsh environments such as the Moon. Our previous work focused on space-filling solids as the module shape for both structures and robots, concluding that the truncated octahedron is optimal, and we have proposed structures and robots modularized into this shape [8]. We also developed a method for geometrically determining module configuration and orientation without complex calculations by exploiting the space-filling properties of the shape [9]. The key contribution of this proposal is that it establishes a unified platform in which module development, configuration, and orientation can all be determined geometrically.

Furthermore, we have proposed an assembly method in which structural modules are incorporated into the robot itself. The robot climbs the structure while leaving part of its body in place, taking advantage of the fact that the structure and the robot share the same geometry. We also conducted a geometric analysis of the module configurations required to achieve the necessary modules and motions [10].

Realizing the proposed method requires a newly designed module that enables the structural module to function as a robot component. In this paper, we report hardware verification results for the assembly operation, a key part of the construction method, using this prototype. The results support the feasibility of our approach.

II. RELATED WORKS

As preliminary research on modular robots designed for module assembly, there are homogeneous robots, such as M-Blocks [11], which are composed of modules of the same shape and function, and heterogeneous robots, such as those proposed by Abdel-Rahman et al. [12], which consist of modules with different shapes and functions. Homogeneous modular robots offer the advantage of simpler design and control due to their uniform structure, whereas heterogeneous modular robots can perform more complex movements and tasks by combining modules with varied capabilities.

In this study, we propose a modular robot that combines the advantages of both approaches: modules with different functions but the same shape. This design enables functional diversity while maintaining the geometric uniformity necessary for efficient configuration and assembly.

III. CONCEPT OF THE MODULAR ROBOT SYSTEM

In this study, we propose a method for constructing high-rise structures—such as vertical solar arrays—using modular robots composed of modules that share the same shape but have different functions. This chapter outlines the modular robots we have developed to date and explains the method used to determine the connection structure of the modules.

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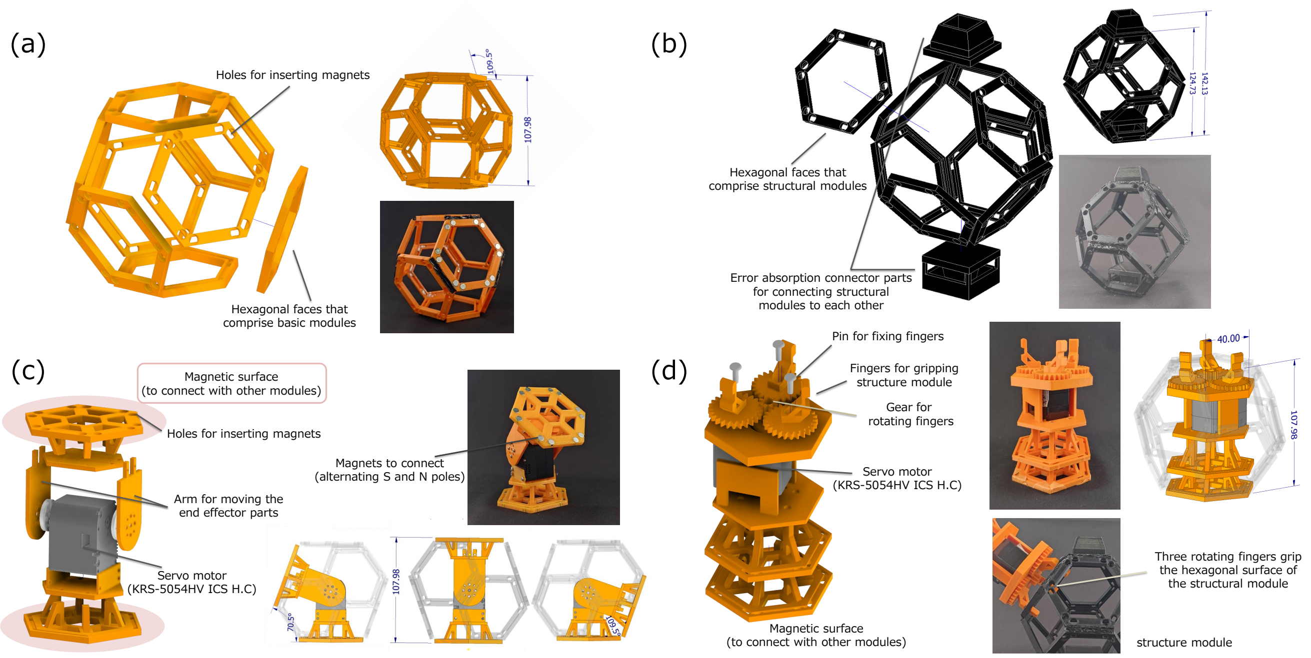


Fig. 1. Truncated octahedron modules ((a) Basic module: Module that supports the robot's link section (b) Structure module: Structure to be assembled; structures are connected via error-absorbing connector parts (c) Joint module: Module that supports the robot's joint section (d) EE (End-Effector) module: Module for connecting the structure and robot)

A. *Shape of the module*

In this study, in order to modularize both the structure and the robot, all modules were designed with the same geometric form. Therefore, the authors have examined the shape of the modules from both the robot's perspective and the structure's perspective. Considering that three-dimensional shapes with spatial filling properties are from the perspectives of connectivity and rigidity, we proposed four types of modules, including robots and structures, with a truncated octahedron shape [8] [9]. The modules proposed so far are shown in Fig.1, and this section explains the details of each module.

Regarding inter-module connection strength, in principle the design should consider the member strength of each module and employ actuator-based coupling mechanisms. At the current prototype stage, however, we use magnets to realize a simple connection between robot modules. In the experiments reported here, only the structural modules are connected and separated; therefore we assume no magnetic coupling for structural modules.

Basic Module(Fig.1 (a)) – This is the module that supports the robot's link section and serves as the basic shape. It consists of eight parts with hexagonal faces, forming a truncated octahedron shape, with 12 magnets (six S poles and six N poles) embedded in each face at each vertex. These magnets enable the module to be connected to other robot modules.

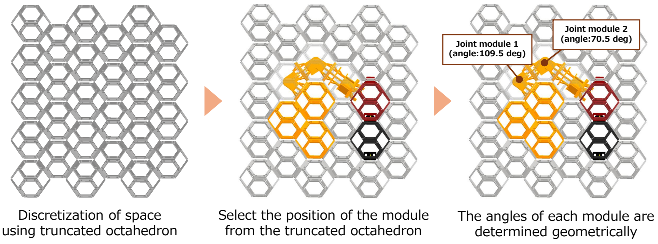
Structural Module(Fig.1 (b)) – Similar in shape to the Basic Module, but without embedded magnets. Instead, connector parts are attached to the square faces to enable error absorption when connecting structures to each other.

Joint Module(Fig.1 (c)) – This module supports the robot's joints. It has one servo motor and two coupling surfaces that enable connection to other modules via magnets. With the coupling surfaces parallel set as $0[deg]$, it has a range of motion of $109.5[deg]$, which is the angle formed by the truncated octahedron faces in the positive and negative directions. At first glance, this module may not appear to have a truncated octahedron shape. However, as can be seen in the figure, when $\theta = -70.5, 0, 109.5[deg]$, the coupling surfaces coincide with part of the faces of a truncated octahedron, so it can be considered to have a truncated octahedron shape.

EE (End-Effector) Module (Fig.1 (d)) – Designed to connect the robot to the structure. This module is equipped with one magnetic connection surface, one servo motor, and an EE part consisting of a three-finger gripper driven by the servo motor. By rotating and opening/closing the three-finger gripper, the structure can be grasped and connected as shown in the figure. Although this module does not appear to have a truncated octahedron shape at first glance, the distance from the coupling surface to the gripping point is the same as the distance between the opposite faces of a truncated octahedron, and it can be interpreted as having a truncated octahedron shape.

B. *Module configuration determination method*

In this study, we have also proposed a method for geometrically determining the combined configuration and positional posture of the modules described in the previous section during operation [9]. In this section, we will explain this method. The truncated octahedron used for the module



Discretization of space using truncated octahedron

Select the position of the module from the truncated octahedron

The angles of each module are determined geometrically

Fig. 2. Module configuration determination method(First, the space is discretized into truncated octahedrons. Next, the position of the module is selected from among the truncated octahedrons according to the operation. This determines the angle of the module geometrically.)

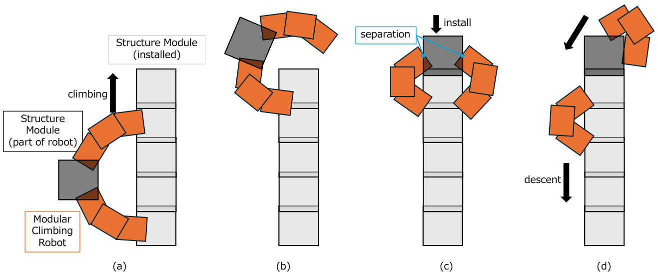


Fig. 3. Proposed construction method ((a) Climb structures already constructed as a single robot (b) Once the highest point is reached, straddle it (c) Assemble the structural modules that were part of the robot into the existing structure, separating the structural modules from the robot (d) Descend as two robots)

shape has space-filling propvererties. Therefore, the space is discretized using truncated octahedrons, and the position of each module is selected from among them. By repeating this process from the initial posture to the target posture, the transition postures can be quantized, and the angles of each module at each posture can be geometrically determined without complex calculations. In this paper, we refer to this method as the module configuration determination method. An overview of the method is shown in Fig.2.

The authors have previously used this method to determine the configuration and positional posture of modules for assembly and climbing motions, and conducted actual machine experiments using the modules described in the previous section. This demonstrated the effectiveness of this method and the modules described in the previous section [9].

IV. PROPOSED CONSTRUCTION METHOD

As mentioned in Chapter 1, the objective of this study is to construct high-rise structures using modular robots. To this end, the authors have proposed a method for construction using the modules described in the previous chapter [10].

In general, climbing the already installed structure requires an inchworm-like configuration for locomotion, whereas assembly at the highest point requires an arm-like configuration for manipulation. Naively combining these functions increases the number of robot modules and the overall mass. Our method avoids this by using structural modules as part of the robot and, while climbing, detaching a portion of the robot and installing it at the top of the existing structure to complete the assembly. This climb-to-assemble strategy reduces the number of dedicated robot modules and suppresses mass growth. An overview of the method is shown in Fig.3. To implement this method, it is necessary to use the structural modules as part of the robot. However, since the structural modules must be separated during assembly, magnetic coupling is not feasible. Therefore, the authors proposed an EE (End-Effector) part-equipped joint module, the EE-joint module, for coupling with the structural modules, and applied the module configuration determination method using this module to determine the module configuration and position/orientation required to realize the proposed construction method [10]. This is shown in Fig.4. In this paper, we report on the design and prototype fabrication of this EE-joint module, and the results of the actual machine verification of the proposed assembly operation using it.

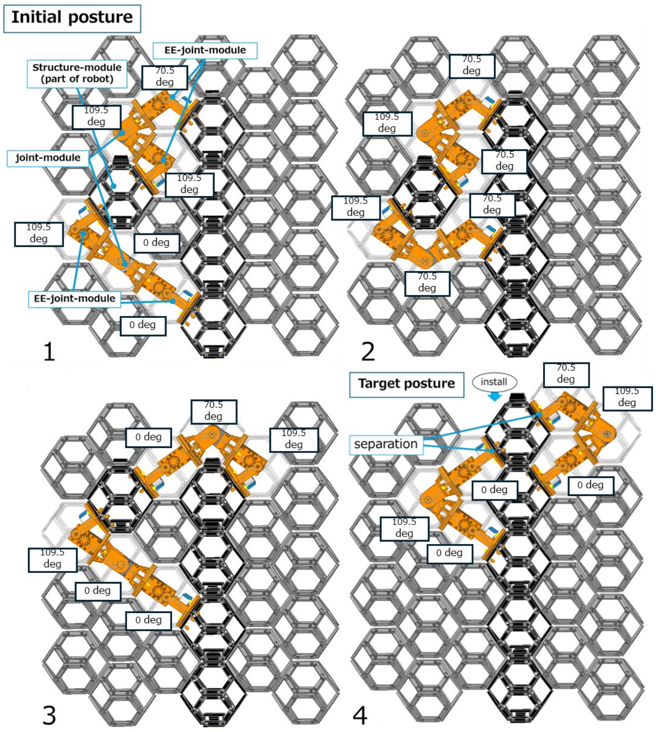


Fig. 4. Module configuration for implementing the proposed construction method (Partially modified from [10])

V. EE(END-EFFECTOR)-JOINT MODULE

This chapter describes the newly designed and prototyped EE (End Effector)-joint module. Details are shown in Fig.5. As shown in (a) of the figure, the EE-joint module consists of an End Effector part for gripping structures, a joint part that serves as the robot's joint, and a magnetic surface for connecting to other modules. The End Effector part is equipped with a 3-finger gripper and is driven by a stepping motor via a gear to open and close. The joint part is driven by a single servo motor and, like the joint module, has a range of motion of $109.5[deg]$, which is the angle formed by the faces of a truncated octahedron, with the connection surface parallel to $0[deg]$. In order to maintain the truncated octahedron shape common to other modules, the drive axis

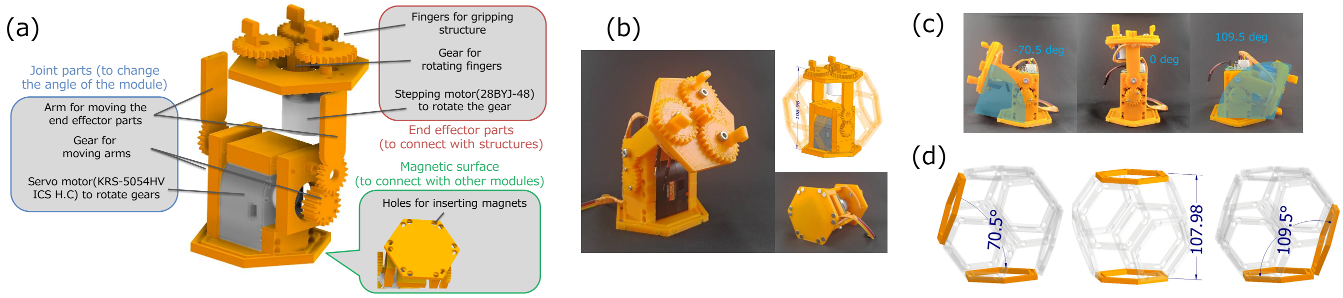


Fig. 5. Details of the EE-joint module ((a) EE-joint module configuration diagram, (b) prototype produced using a 3D printer, (c) joint driving a part of a truncated octahedron, (d) face of the truncated octahedron formed at the angle in (c))

of the joint must be positioned at the center of the module despite space constraints. Therefore, the servo motor is positioned away from the EE part to avoid interference with the stepper motor, and the drive axis is positioned at the center of the module via a gear. The joint surfaces, like those of other modules, have S-pole and N-pole magnets pressed into each vertex, maintaining symmetry. The prototype is shown in Fig.5 (b). It was manufactured using PLA resin with a 3D printer. Additionally, as shown in (c) of the figure, when $\theta = 0, 109.5, -70.5[deg]$, it aligns with part of the face of a truncated octahedron, as shown in (d) of the figure, and can thus be considered to have the shape of a truncated octahedron.

Furthermore, the EE parts of the EE-joint module are basically constructed in the same way as the EE module. However, problems were observed when combining the structural module using the conventional EE module. This was due to the fact that there were many recesses in the fingers of the EE part, causing the surface of the structural module to become stuck in the recesses during the combination or when releasing it.

Since this issue is believed to be resolvable by modifying the shape of the fingers, the current EE-joint module has undergone a design change to the finger shape. The connection between the conventional parts and the improved parts is shown in Fig.6. As shown in the figure, unnecessary concavities have been eliminated, and the surfaces now make direct contact with the connection surfaces. The effectiveness of this modification will also be verified through actual machine experiments.

VI. EXPERIMENTAL SETUP AND METHODOLOGY

Using the EE-joint module described in the previous chapter, we conducted a actual verification of the proposed assembly operation. The purpose of this experiment is to verify the proposed construction method, the module configuration determination method, and the effectiveness of the EE-joint module. As the first stage of the actual verification, we verified the operations 3 to 4 shown in Fig.4. In this chapter, we describe the experimental setup and methods.

The structural modules to be climbed are fixed to the optical table via fixtures, as shown in Fig.7(a). The structural modules are also fixed to each other in advance before the robot is attached. The robot modules are connected by magnets, and the structural modules are connected by end effectors. The configuration and initial posture of the connected modules are shown in Fig.7(b). This posture is based on geometrically determined angles, as described in Chapter 3. (Fig.4(3))

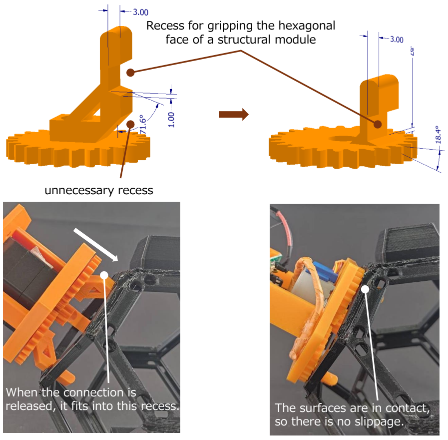


Fig. 6. Comparison between conventional EE module fingers (left figure) and improved EE-joint module fingers (right figure)

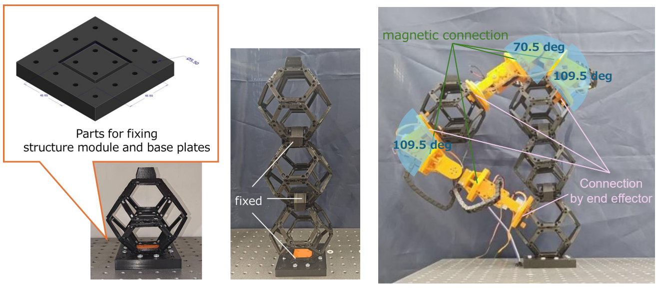
From this initial posture, we performed actual machine verification with the motion shown in Fig.4(4) as the target posture.

In future work we will generate collision-aware trajectories; in this work the trajectory from the initial to the target posture was determined by arbitrary waypoint specification.

VII. EXPERIMENTAL RESULTS

The results of the first actual machine verification are shown in Fig.8. In this experiment, the structural module was attached to a part of the robot and an attempt was made to climb, but as can be seen in the photo, when the lower EE was separated for climbing, the weight of the robot body caused the attachment surface of the module to separate.

The results of the next experimental verification with improved operation are shown in Fig.9. In this experiment, the module configuration was unchanged, but during climbing, the structural module, which is part of the robot, was made to intentionally contact the existing structural module to attempt



(a) (b)

Fig. 7. Experiment setup ((a) The structure module is fixed to the base plate using a fixture. The structure module to be climbed is also fixed on top of it. (b) The robot was attached to the fixed structure module in its initial position. This position was geometrically determined.)

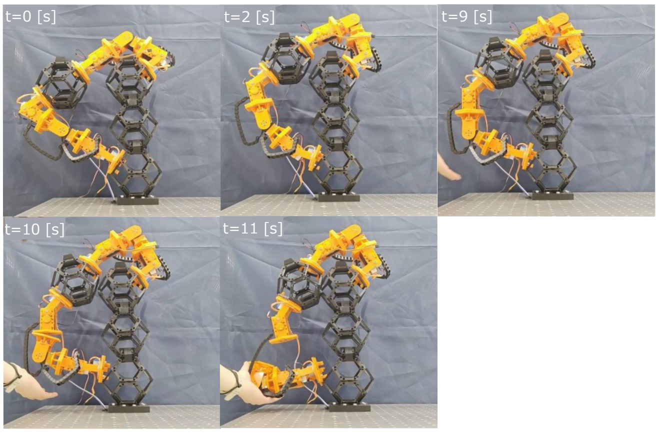


Fig. 8. Experiment 1 result (When the lower EE-joint module was separated and became a single-point support, part of the module separated and failed.)

to distribute the robot's weight. This increased the number of contact points between the robot and the structure from two to three, distributing the weight and preventing the EE from separating. As a result, as shown in the photo, climbing was performed, and the assembly of the structural module, which was part of the robot, at the top was successfully achieved.

VIII. DISCUSSION

The experimental results showed that climbing and assembly are possible by using the truncated octahedron module robot proposed in this study and incorporating structural modules into the robot.

As can be seen in Fig.9, no problems were observed in terms of the EE part's fingers getting stuck during connection and separation.

This shows that the finger shape changes described in Chapter V are advantageous. Additionally, the effectiveness of the module configuration determination method using spatial filling proposed in this study was demonstrated, as the proposed method successfully achieved the desired motion in both the initial and target postures.

Another factor contributing to the success of this operation was the truncated octahedron shape of the modules. As mentioned earlier, in Experiment 1, when the lower EE-joint module was separated, the robot fell into a state of single-point support at the joint of the upper EE-joint module. This caused the modules to separate due to the weight of the robot body. Therefore, in Experiment 2, before separating the lower EE-joint module, we intentionally caused the structural module located at the center of the robot to contact the existing structural module, ensuring that a two-point support condition was maintained even after separation. As a result, the modules did not separate, and the robot was able to perform the intended operations of climbing and assembly. From this, it can be considered that the robot's load was distributed by maintaining a two-point support state. This action of deliberately contacting the structural module was made possible by the fact that the module was shaped like a truncated octahedron and had uneven surfaces. If the module had been shaped like a cube with flat sides, such contact would have been difficult to achieve. This is one of the reasons why a truncated octahedron is a suitable shape for the module. In addition, the initial posture and target posture for this action were determined using the module configuration determination method proposed in this study.

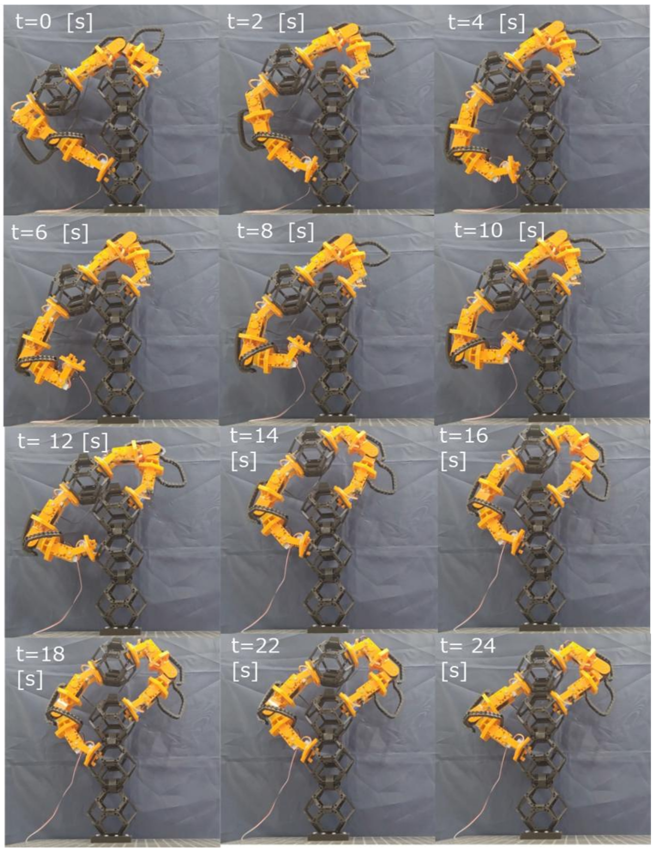


Fig. 9. Experiment 2 result (To improve operation, the structural module, which is part of the robot, was brought into contact with the existing structural module before separating the lower EE-joint module. This enabled constant two-point support. After that, the topmost part was reached and the structural module was assembled.)

Additionally, the initial and target postures for this action were determined using the module configuration determination method proposed in this study. By determining the posture using this method, the transition postures for a given action can be quantized into “spatially filling postures”. Currently, postures are selected arbitrarily from among those that satisfy spatial filling, but in the future, this posture selection will be optimized by focusing on the required torque of the motor. Specifically, the module connection points are defined, and postures are explored using the module configuration determination method. Next, it is determined whether the explored postures can transition between each other. Then, we treat the posture transition from the initial posture to the target posture as a graph by connecting the transitionable nodes with edges, with the postures as nodes. At this time, we assign the static torque of the posture as the cost to the nodes and the motion torque required for transition as the cost to the edges, and optimize the route with the smallest total cost. The formula is shown below.

Let the set of paths be

$$\mathbf{A} = \{a_0, a_1, \ldots, a_m\},$$

the set of nodes included in the path be

$$\mathbf{a}_n = \{q_0, q_1, \ldots, q_k\},$$

the set of edges included in the path as

$$\mathbf{a}_e = \{(q_0, q_1), (q_1, q_2), \ldots, (q_{k-1}, q_k)\}$$

and

$$\begin{aligned} x^* &= \arg \min_{x \in \{0,1,\ldots,m\}} (\tau(a_x)) \\ \text{where} \quad \tau(a_x) &= \sum_{q_i \in \mathbf{a}_n} \tau(q_i) + \sum_{(q_i, q_{i+1}) \in \mathbf{a}_e} \tau(q_i, q_{i+1}) \end{aligned}$$

By determining the transition posture in this way, we believe that it is possible to achieve long-lasting operation, which is important in extreme environments such as the moon.

IX. CONCLUSION

In this paper, we described the method of module construction using the truncated octahedron module-type robot proposed in this study and the modules that have been created so far. We also described the details of the actual robot, including a new prototype of the EE-joint module, which is necessary for the proposed method of assembly using structural modules as part of the robot and leaving those structural modules in place.

We validated the proposed assembly operation through hardware testing with the newly developed modules. The results confirmed that the assembly of structural modules integrated into the robot is feasible. During these experiments, we also identified an additional advantage of using truncated octahedron shapes: their geometry facilitates stable contact and load distribution, contributing to successful climbing and assembly. These findings demonstrate the effectiveness of the proposed modular robot, the module configuration determination method, and the overall construction approach.

By determining module configuration and posture based on space-filling properties, the postures can be quantized, enabling the development of algorithms for optimal posture transitions. Future work will focus on implementing such algorithms and conducting physical experiments covering the entire sequence from climbing to assembly and descent. Beyond single-module assembly, subsequent experiments should include scenarios where the robot separates, descends, retrieves a new module, and reintegrates it into the system.

Looking ahead, while the primary aim of this research is to propose a construction mechanism suitable for extreme environments where heavy machinery cannot be used—such as the lunar surface—further development must address real operational conditions. Key considerations include the effects of lunar gravity, dust resistance, and the selection of materials capable of withstanding sudden temperature fluctuations.

Through these measures, the proposed method can evolve into a sophisticated technology platform that will play a pivotal role in advancing space system integration.

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