

Meta-module Mutual Assistance: A Bio-inspired Design for Self-assembly of Modular Space Robot

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Abstract

The theoretical capability of modular robot to organize the overall robot into different structures with different functions has broad prospects in space exploration. Therefore, we develop a novel modular space robot named Space Module, and inspired by biological cooperative and mutual assistance behaviors, a novel self-assembly method is proposed for it. To solve the mobility problem of non-mobile modules, a new meta-modules design for Space Module is presented, based on which the concept of mutual assistance is utilized to achieve position and posture reachability of assembled unit while minimizing the effect of meta-modules on granularity. Then, an assembly planner is designed to obtain the assembly sequences according to the unique motion characteristics of meta-module and mutual assistance to realize the self-manufacturing of desired configurations. Finally, several demonstrations are given to verify the validity and feasibility of the proposed assembly method.

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ToC Figure

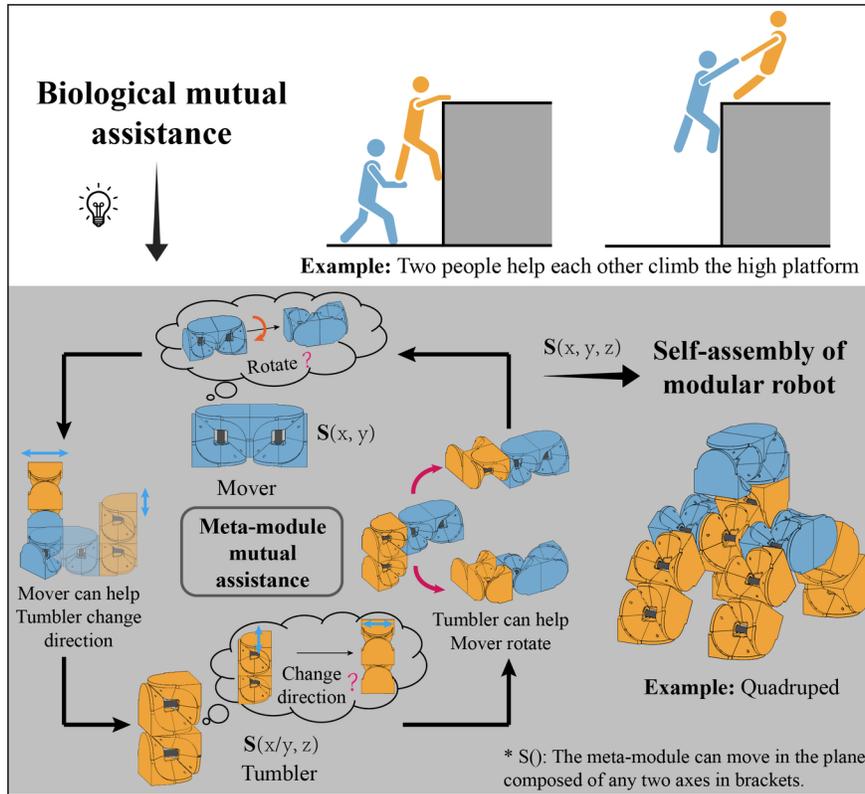


Figure 1: **ToC Figure.** [Biological mutual assistance is an interesting phenomenon in swarm intelligence, creatures with insufficient capacity help each other to achieve their goals. In this paper, this concept is applied to Mover and Tumbler, two types of meta-modules with limited mobility. By helping each other, each meta-module can obtain full locomotion ability, which will be used to realize self-assembly of modular robot.]

Introduction

Cooperative nest construction by social insects (Hansell, 2007; Invernizzi and Ruxton, 2019) such as termites and wasps is common in biological kingdom, natural builders demonstrate significant degrees of cooperation ability and efficiency. These behaviors have highly heuristic meaning to collective construction of multi-agents system, which received more and more attention from scholars (Zhang et al., 2022; Petersen et al., 2019). It is worth noting that the self-assembly behavior of modular robots is also a special construction process of multi-agents.

Modular robot is a class of special robot, which is composed of several homogeneous or heterogeneous modules with certain drive and sensing ability (Holdcroft et al., 2022). Through the combining and disassembling modules, modular robot can be organized into different structures with different functions to adapt to complex tasks and environments (Yang et al., 2022; Zhang et al., 2020). With the rapid development of aerospace technology, modular robot has begun to turn their attention to space exploration (Sayed et al., 2022; Toglia et al., 2011), such as building the adaptive and unmanned robotic system for lunar base. The special micro-gravity environment can help modular robot get rid of the limitations of module size on joint drive capability, which will make large-scale module movement and reconfiguration possible. At the same time, the complex space environment and diverse customizable tasks also make the advantages of modular robots useful. Therefore, we develop a novel modular robot named Space Module for the special space

environment. Constrained by the payload capacity of spacecraft, Space Module is designed with a light and regular structure and is non-mobile. To reduce the failure rate of module, the complex mechanical structures are abandoned, and the electropermanent magnets are used for docking, communication and charging.

Self-assembly is one of the ways for modular robot to realize shape-shifting. The autonomous aggregation of dispersed, initially-detached modules into desired morphologies (Wei et al., 2012) is similar to the cooperative nest construction of insects, with the subtle difference that the modules are both transporters and materials for construction. Compared to other schemes (Bie et al., 2019; Gerbl and Gerstmayr, 2022; Luo and Lam, 2022), self-assembly is not limited by system connectivity and the module number of current configurations. Therefore, considering the possible dilemmas suffered by robotic systems in unmanned operating environments, such as module separation due to impact or fall, autonomous disengagement and replacement of faulty modules, self-assembly is the preferred shape-shifting method for modular space robots.

Some results have been obtained for the research on self-assembly of modular robot. (Li et al., 2016) proposed a formation self-assembly method for Sambot modular robot, which can self-assemble a group of swarm robots into a single articulated structure; (Ercan and Boyraz, 2016) presented a chain type, homogenous, mobile and modular multi-robot system (ULGEN), and used the mobility and sensors of modules to realize the self-assembly of desired configurations; (Wei et al., 2012) proposed a directional self-assembly control model which utilized the seed module and docking module to perform the self-assembly experiments; (Rai et al., 2011) proposed a suite of algorithms for REPLICATOR modular robot, including a reversible graph grammar and broadcast communication, which can drastically speed up self-assembly process. Noted that these methods are proposed based on mobile modules, which have full locomotion capability and can move independently. Hence, the self-assembly methods of mobile module are more like simplified path planning of multi-agents (Del Dottore et al., 2018). However, the complex mobile mechanics of mobile modules will increase the redundancy of modular robot structures and reduce the robustness, which is not suitable for unmanned space work requirements. The research on self-assembly of non-mobile modules is almost non-existent, and the fundamental problem is the mobility of non-mobile modules. The design of self-assembly using external forces such as water and magnetism in (Zhu et al., 2013; Yun and Rus, 2011; Haghghat and Martinoli, 2017) is still a long way from producing application value.

Meta-modular method is an important breakthrough in modular robot self-reconfiguration and flow motion proposed to give non-mobile modules the ability to move. Meta-module is an intelligent unit of a small group of basic modules, and the locomotion ability of meta-modules is related to the number of modules and docking mode. (Kawano, 2019) studied a reconfiguration algorithm for heterogeneous lattice modular robots with linear operation time cost based on a 2x2x2 cubic meta-module; (Parada et al., 2021) proposed a new meta-module design for two important classes of modular robots, which can perform the scrunch, relax and transfer moves that are necessary in any tunneling-based reconfiguration algorithm; (Brandt and Christensen, 2007) presented a 2D meta-module for the ATRON robot, which simplifies the motion constraints significantly, and utilized a simple distributed algorithm to achieve efficient cluster flow locomotion; (Yang et al., 2018) proposed a novel self-configuration strategy based on the concept of meta-module, which can make every meta-module self-configure in the system by itself and the global constraints are effectively reduced at the same time. Those results provide inspiration for the self-assembly of non-mobile modules, but there are still some problems. In order to obtain sufficient locomotion ability, it is necessary to increase the assembled granularity, hence the meta-module is irregular and oversized, which will severely affect the diversity of organizable configurations.

Biological mutual assistance is an interesting phenomenon in social animals, organisms help each other to achieve tasks that cannot be completed by each other alone, so as to achieve a win-win situation. For example, when two people want to climb a high platform, the most appropriate measure is that one person first supports the other person to climb up, and then the upper person pulls the lower person up. Inspired by this, a mutual assistance assembly scheme based on meta-module is proposed. Meta-modules receive or provide assistance to each other while traveling to the assembly site, which can be used to help meta-modules designed compensate for the lack of mobility and minimize the impact of meta-modules on granularity. Then

an efficient assembly planner is designed based on the motion characteristics of meta-module and mutual assistance to obtain the assembly sequence of target configuration and realize the self-manufacturing of a class of configurations. This meta-module mutual assistance method will make a good start for the building of adaptive and unmanned robotic system for lunar base. Finally, several simulation examples are given to demonstrate the feasibility and effectiveness.

Experimental Section/Methods

1. Space Module

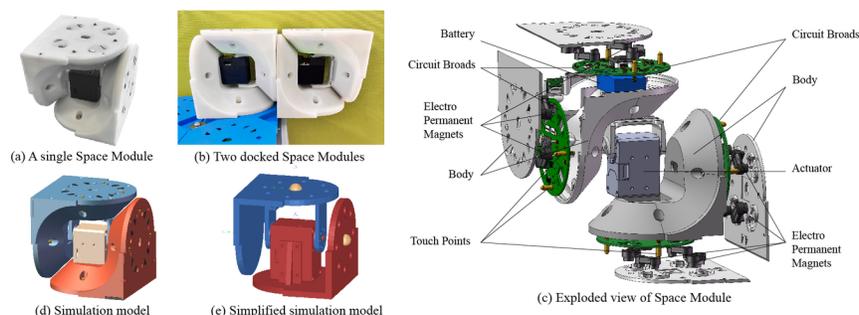


Figure 2: Space Module

Space Module is a 100x100x100 mm cube, which is regular and compactness. Each module has four connection surfaces and one degree of freedom, which can be used to form different robot configurations with different functions. Docking method adopts electropermanent magnet, which can be used for posture judgment and communication. 70 N attachment force can be maintained. Each module has a lithium-ion polymer battery, a micro-controller and a 2.4GHz NRF24L01 transceiver module unit. The cluster of modules is controlled by a central computer running a Python program that sends serial commands to control the degrees of freedom, magnet on/off and communication of each module. The wireless network is provided by a wireless serial port with a range of about 20m, allowing high-speed communication between the modules and the host computer. In addition, each module has infrared sensor and IMU to measure distance and feedback acceleration.

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2. Meta-module

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3. Mutual assistance

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4. Self-assembly planner

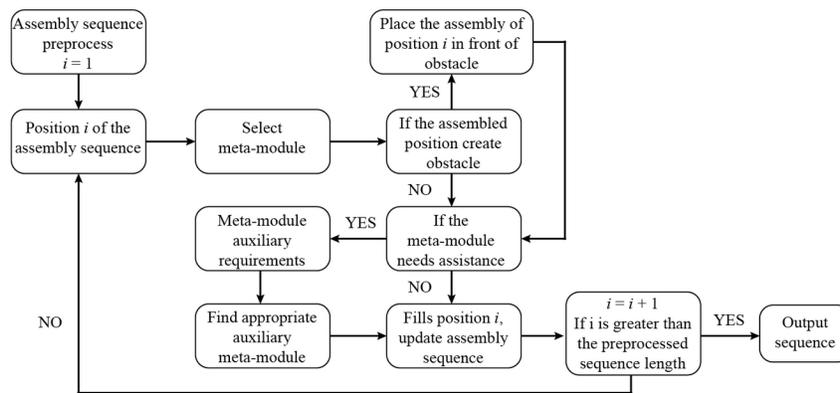


Figure 3: Assembly planning flowchart.

A bubble algorithm is proposed for Space Module to achieve self-assembly, whose principle is to replace the order of the meta-module whose movement is obstructed to the front, and continuously update the whole assembly sequence until a suitable one is found.

Results

1. Super redundant manipulator

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2. Quadruped robot

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3. Humanoid robot

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Discussion

1. Meta-module mutual assistance

In past research, there is a tendency to add enough designs to the unit robot to make it omnipotent. The most direct manifestation in the meta-module is the increasing number of modules, which will make its structure large and complex, with redundant functions and increased failure rate. Table 1 shows the characteristics of some representative meta-modules.

Through comparison, it can be clearly seen that the granularity of the meta module proposed by our group is optimal. It is composed of only two basic modules, with regular and compact shape and strong motion ability. Although such a comparison is unfair, because the structural characteristics of the unit modules and the different target tasks will lead to a certain differences in the design of the meta-modules, it can be seen that the superiority of the mutual assistance. In order to meet the carrier weight and space requirements of launch vehicle and reduce the potential for mechanical failure, the module was designed to be extremely simple, with only two L-shaped surfaces and a revolute joint. Hence, stronger mobility means that more modules should be combined and two modules are far from enough. As shown in previous description of Mover and Tumbler, both of them have motion defects. However, through mutual assistance, full mobility is achieved, and the granularity of the meta modules remains at the size of two modules. Therefore, mutual assistance is of great significance to the research of non-mobile modules, which is a further improvement on the meta-module method.

2. Self-assembly of Space Module

Based on the premise assumption that it is necessary to place the cargo in a centralized and regular manner during the rocket launch process, the initial stacking form of meta-modules is shown in Figure 11, Figure 12 and Figure 13 . Although they are stacked together, the meta-modules are separated from each other, which is not fundamentally different from the scattered distribution, and will not affect the self-assembly process.

In the self-assembly process, the required meta-modules are driven out from the library in turn and move to the assembly position assigned to them. During the movement, there will be corresponding meta-modules to assist them to change direction or rotate. When all meta-modules reach the target positions, joint postures are adjusted uniformly to ensure reliable connection surfaces. Finally, the assembly configuration can be

Table 1: Representative meta-modules

Module	Number	Structure	Function	Application
Sliding Cube ^[21]	4	Pyramid	Tunneling motion	Self-reconfiguration
Molecube ^[25]	60	Irregular	Crystalline atom operations	Self-reconfiguration
M-TRAN ^[22]	16	Irregular	Tunneling motion and Crystalline atom operations	Self-reconfiguration
ATRON ^[23]	4	Square	Movement	Self-reconfiguration
ATRON ^[26]	3	Triangle	Sliding cube movement	Flow
M-Lattice ^[24]	2	Rectangle	Rotation	Self-reconfiguration
Space Module	2	Cuboid	Movement and Rotation	Self-assembly

assembled, and then the quadruped robot, humanoid robot and Super redundant manipulator are formed by adjusting the joint angles.

The situations contained in the experiments is comprehensive. Firstly, it contains all the motion forms of the meta-modules, including the tumbling motion of Tumbler, the movement of Mover and the tumbling motion of Rotated Mover. Secondly, it contains all forms of mutual assistance, including Mover helping Tumbler to change its forward direction and Tumbler helping Mover to rotate. Finally, it contains various positions and postures in the target configurations, including horizontal or vertical placement and different rotation angles. Hence, the above experiments are a strong proof for the effectiveness of the self-assembly method proposed in this paper.

Conclusion

The concept of meta-modules mutual assistance is proposed inspired by biological cooperation and mutual assistance, which makes non-mobile modules no longer need to seek a balance between granularity and mobility. Then an assembly planner is designed to achieve autonomous assembly while avoiding assembly conflicts and positional blockage. Some experiments demonstrate the effectiveness of the method. Through this method, the self-manufacturing of various robots can be realized, which will make a good start for the development of the unmanned and adaptive robotic system of the lunar base.

In next work, hardware experiments will be refined and an attempt will be made to apply to a specific task, and then the assembly strategy will be further optimized to reduce the constraint of the configuration using the method of configuration decomposition and component assembly. In addition, the method of meta-module mutual assistance has high application value in the fields of self-reconfiguration and self-repair, which is worth further exploration.

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Conflict of interest

The authors declare no conflicts of interest.

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