Freeform Modular Robots: Reconfigurability via Swarm Spheres

Guanqi Liang
The Chinese University of Hong Kong, Shenzhen

I. Introduction

Modular self-reconfigurable robot (MSRR) systems consist of multiple modules that can dynamically alter the system's morphology by modifying inter-module connections and spatial configurations, enabling adaptation to diverse tasks and environments [29]. Previous research indicates that MSRR systems are particularly effective in complex terrain exploration [27, 23, 12], object manipulation (including obstacle avoidance [31], handling [20], grasping [30], and transportation [23]), and programmable material applications [14, 32], such as reconfigurable furniture [19, 5]. Furthermore, MSRR systems hold considerable potential for use in modular building construction [24], space exploration [2, 33], and general robotic development [3], with the prospect of evolving into highly adaptable "general-purpose robots" [29]. However, traditional MSRR systems generally exhibit significant homogeneity, being primarily composed of cubic modules equipped with joint actuators. These cubic modules present two key drawbacks. First, the connection process between modules poses substantial challenges, requiring precise alignment of their faces [4, 32, 28, 15, 1], which is not only time-consuming but also results in a low success rate. This limitation severely restricts the efficiency of module assembly and the overall flexibility of the system. Second, the connection points for these modules are fixed [26, 6, 13, 15, 16], significantly limiting their configuration and mobility. Additionally, the range of motion, direction, and degrees of freedom provided by the joint actuators are relatively constrained [13, 6, 17, 18, 21], further limiting the system's movement potential.

To address these challenges, my research objective is to develop an MSRR system that enhances the speed, fault tolerance, robustness, and intelligence of robotic reconfiguration (Fig. 1). The contributions of my work can be summarized in two main aspects: 1) the development of an innovative mechanism that enables rapid, fault-tolerant, and flexible connections, and 2) the further exploration of sensing, modeling, and stability analysis of this new robotic platform, thereby achieving a dexterous, versatile, and robust robotic system. Specifically, inspired by the Buckyball building block toy, my research introduces a freeform docking technology for MSRR systems that eliminates the need for precise alignment [8, 7]. By using spheres and magnets, this approach facilitates rapid and fault-tolerant connections between modules, enhancing the variety of morphologies that can be formed through module combinations. Furthermore, the internal drive mechanism enables dexterous dynamic movement. These features significantly surpass the capabilities of traditional cubic modular robots. Building on this new robotic platform, my further research addresses critical aspects such as modeling [31], sensing [22], energy [9], and control [31, 12], with the goal of advancing this technology from a laboratory prototype to practical applications.

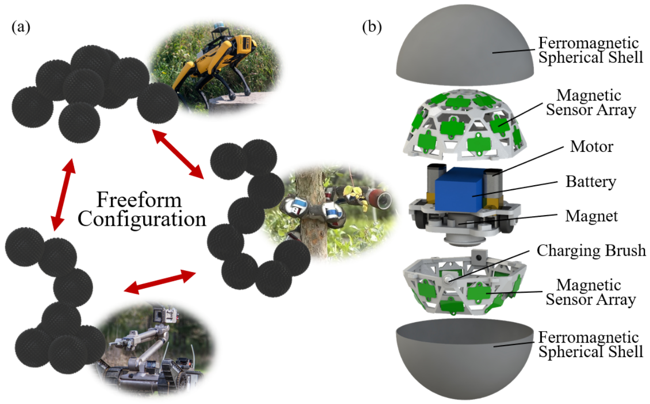

Fig. 1. (a) Freeform modular robot system capable of forming diverse shapes and adapting flexibly. (b) Structure of the freeform modular robot, where each module contains a ferromagnetic sphere and an internal drive trolley with a magnet and sensor array, enabling rapid, fault-tolerant connections and dexterous movement.

II. Contributed Research

A. *Enabling Rapid, Fault-Tolerant, and Flexible Connections*

1) ***Freeform Docking Mechanism*** *[8, 7]:* The core contribution of my research revolves around the connection technology of unconstrained continuous connection, and the freeform modular robot was developed based on this. The core method is to achieve free and fast connection and disconnection between modules through magnetism. Each module comprises a ferromagnetic spherical shell and an internal driving trolley (Fig. 1(b)). The trolley is equipped with a bottom-mounted magnet, allowing the module to establish continuous connections with other modules in any direction or position. This design provides a high tolerance for positional errors, overcoming the constraints of traditional modular robots that require precise connection points and alignment. The internal trolley is powered by two DC motors, which enable adjustment of its position, altering both the center of gravity and the magnetic field interaction. All movements – connection management, individual mobility, and relative positioning – are facilitated by the two motors, ensuring efficient motion control. This research significantly enhances the flexibility, fault tolerance, and reconfiguration efficiency of modular robots. Furthermore, the proposed design reduces complexity and cost, while offering strong scalability and the ability to adjust the robot's scale and form based on task requirements.

*2) **Spherical Gear Structure** [10]:* While the spherical design of the freeform modular robot offers significant flexibility, it also presents challenges in terms of robustness. Specifically, point contact between the spheres can easily lead to slippage, disrupting the relative movement between modules. To address this issue, this research adapted the principles of traditional gears and introduced the concept of spherical gears, extending conventional plane gears into three-dimensional space. The research first achieves both latitudinal and longitudinal meshing of the spherical gear, then integrates these meshing techniques to enable global meshing across the entire sphere. Furthermore, spherical gear prototypes with varying parameters and sizes were developed. Tests and experiments demonstrated that the spherical gears successfully enabled non-slip rolling between the spheres, effectively resolving the slippage issue in the freeform modular robot. Additionally, the relative rolling motion between spheres enabled wide flexibility, showing strong potential for robotic joints.

*3) **Reimagining MSRR Taxonomy** [11]:* While developing the freeform modular robot and continuously comparing it with traditional modular robots, I began to explore the underlying logic of MSRR mechanisms. To address this, we conducted an extensive survey into the various mechanisms and design aspects of MSRR systems and proposed an new unified conceptual framework to understand MSRR hardware. This framework consists of three key elements: connectors, actuators, and homogeneity. Using this tripartite framework, we systematically explain and classify MSRR systems developed over the years, offering a structured taxonomic perspective that enhances the understanding of MSRR. It highlights the fundamental properties that define MSRR systems and their components, while also providing insights into their design, technology, function, and classification. My research effectively resolves the longstanding taxonomic confusion in the field of MSRR.

B. Towards a Dexterous, Versatile, and Robust Robotic System

*1) **Magnetic State Estimation** [22]:* The sensing of MSRR systems relies on accurately measuring the relative motion between modules, but the spherical shell and virtualized joints of the freeform modular robot present challenges in directly measuring the relative state. To address this, this research leveraged the properties of magnetic connections and proposed a solution based on magnetic field measurement. By positioning a magnetic sensor array on the sphere's surface and integrating it with a graph convolutional network to process the data, precise calculation of the connection point position was achieved. The solution performed effectively during prototype testing, with all calculations handled by an onboard microcontroller, ensuring both lightweight operation and high efficiency. This method not only enables high-precision positioning but also establishes the foundation for closed-loop control and system-level behavior in the freeform modular robot.

*2) **Spherical Rolling Contact** [31]:* The main challenge in freeform modular robot modeling is the unique motion of one sphere rolling on another, which surpasses traditional joint models. To solve this, this research adapted the 1-DOF circular rolling contact from planar gears to three-dimensional space, introducing spherical rolling contact motion. By using a virtual tangent plane, the model was simplified, allowing for broad motion and easier control. A two-stage control approach was developed: upper-level planning determines the expected position and trajectory, while lower-level execution ensures precise control via the trolley inside the sphere. This work introduces spatial rolling contact motion and validates its real-world effectiveness, demonstrating the potential of freeform modular robots for complex motions and controlling dexterous joints.

*3) **Configuration Stability Analysis** [25]:* In modular self-reconfigurable robots, configuration stability significantly impacts system performance, especially in freeform modular robots. To tackle potential instability in their motion, this research propose a linear-time quasi-static stability detection method. This approach models stability as a second-order cone programming problem, accounting for internal connections, non-connected contacts, and environmental interactions, with solution time increasing linearly with the number of modules. The algorithm evaluates system stability, identifies critical stable states, and detects potential disconnection points. Experiments demonstrate the method's effectiveness in predicting stability and pinpointing disconnections across various configurations, offering an efficient and reliable solution for stability analysis in modular self-reconfigurable robots.

III. Future Directions

Building on my research in modular reconfigurable robots, I aim to advance the original freeform robot system and develop an adaptive robot with environmental interaction capabilities. My plan follows a three-phase path: "breakthroughs – enhancements – real-world applications."

In the short term, I will focus on overcoming challenges in modular robot motion planning, integrating embodied intelligence, and developing a distributed autonomous reconfiguration algorithm using deep reinforcement learning. I also plan to build a multimodal perception system with visual sensors to enable dynamic environmental awareness and support morphology optimization for practical applications.

In the medium to long term, I plan to focus on extreme environment applications, considering two main scenarios: 1) developing a robot platform for coal mine tunnels to overcome challenges like low passability and limited functionality in traditional equipment, and 2) creating a self-assembly system for deep space exploration to deploy multi-morphological detection. My goal is to establish a robust modular robot technology system that brings self-reconfigurable robots into real-world applications.

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