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Bonded by Design: Magnetic Modules for Cooperative Tasks

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***Abstract*— Overcoming the physical and functional limitations of single-unit soft robots requires a transition toward modular systems capable of collective cooperation. This work presents a modular magnetic soft robotic platform based on identical, millimeter-scale hexagonal units designed for high-strength assembly and versatile locomotion. The hexagonal geometry is utilized to provide edge-to-edge connectivity, enabling the formation of continuous assemblies without geometric gaps. Each unit incorporates magnetically responsive structures for locomotion, radio frequency-triggered components for localized thermal bonding, and thermally tunable frames for variable stiffness. These features allow individual modules to transition between tumbling and compression-extension modes based on their thermal state. Furthermore, individual modules can self-assemble into robust configurations to perform cooperative tasks, such as bridging gaps and surmounting obstacles that exceed the capability of a single unit. Tensile testing confirms that thermally activated bonding provides significantly higher inter-unit connection strength than magnetic coupling alone, ensuring the structural integrity necessary for collective maneuvers. This modular approach provides a scalable framework for soft robotic collectives capable of complex navigation and cooperative tasks.**

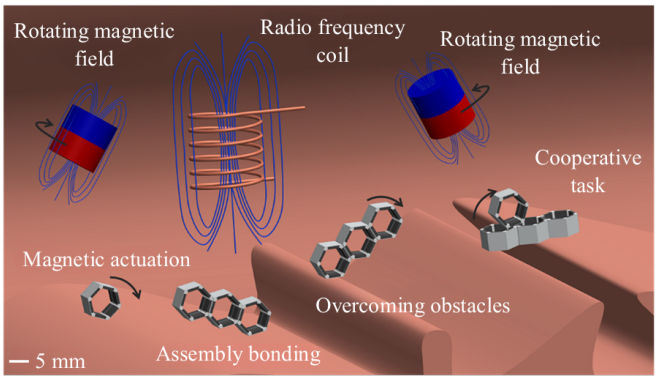


Fig. 1. Hexagonal magnetic module concept: Modules are navigated one-by-one by means of magnetic actuation. Modules can form robust assemblies via radio frequency-triggered bonding. Assemblies of hexagonal modules perform tasks beyond the capabilities of a single module. Under the presence of rotating magnetic fields, assemblies of hexagonal modules support another module in passing a gap. Blue lines indicate magnetic field lines.

I. Introduction

Magnetic soft robots are emerging as a versatile solution for operating in complex and sensitive environments [1], [2]. Owing to their miniaturized and compliant design, magnetic soft robots can access confined spaces that remain inaccessible to their traditional rigid or tethered counterparts [3]. Wireless magnetic control eliminates the need for onboard power or physical connections, substantially reducing mechanical constraints during deployment [4], [5]. Magnetic soft robots are particularly well-suited for performing controlled, localized tasks in confined, complex, and fragile environments. Many magnetic soft robots have been developed for targeted tasks such as cargo delivery [6], [7], [8], [9], [10], [11], localized heating [9], and mechanical manipulation [11], [12]. However, most systems rely on single-unit designs, which limits operational range. Although miniaturization allows operation in confined environments, some tasks exceed the capabilities of a single unit. Coordinated action among multiple agents enables scalable functionality and enhanced performance. Research in modular and collective microrobotics has advanced along two paths: magnetic control strategies and design-based innovations. Tuning magnetic interactions among individual units can create attractive and repulsive forces, producing stable configurations and coordinated motion across centimeter-scale distances [13]. Building on this, self-repelling ferromagnetic microrobots can be guided by spatially and temporally programming an external magnetic potential energy distribution. This distribution can be applied at the air–water interface or on solid surfaces. This approach enables swarm behaviors such as aggregation, directional group motion, and rotational swarming [14]. Alongside control strategies, prior research has explored different designs to enable modular assembly and adaptability. Heat-activated bonding with thermoplastic or solder sites allows magnetically-guided modules to assemble remotely. The assembled modules form locomotable structures with strong mechanical and electrically conductive links [15]. At a larger scale, magnetic units can selectively assemble into diverse morphologies. Units can switch between rolling, walking, or climbing modes under magnetic actuation [16].

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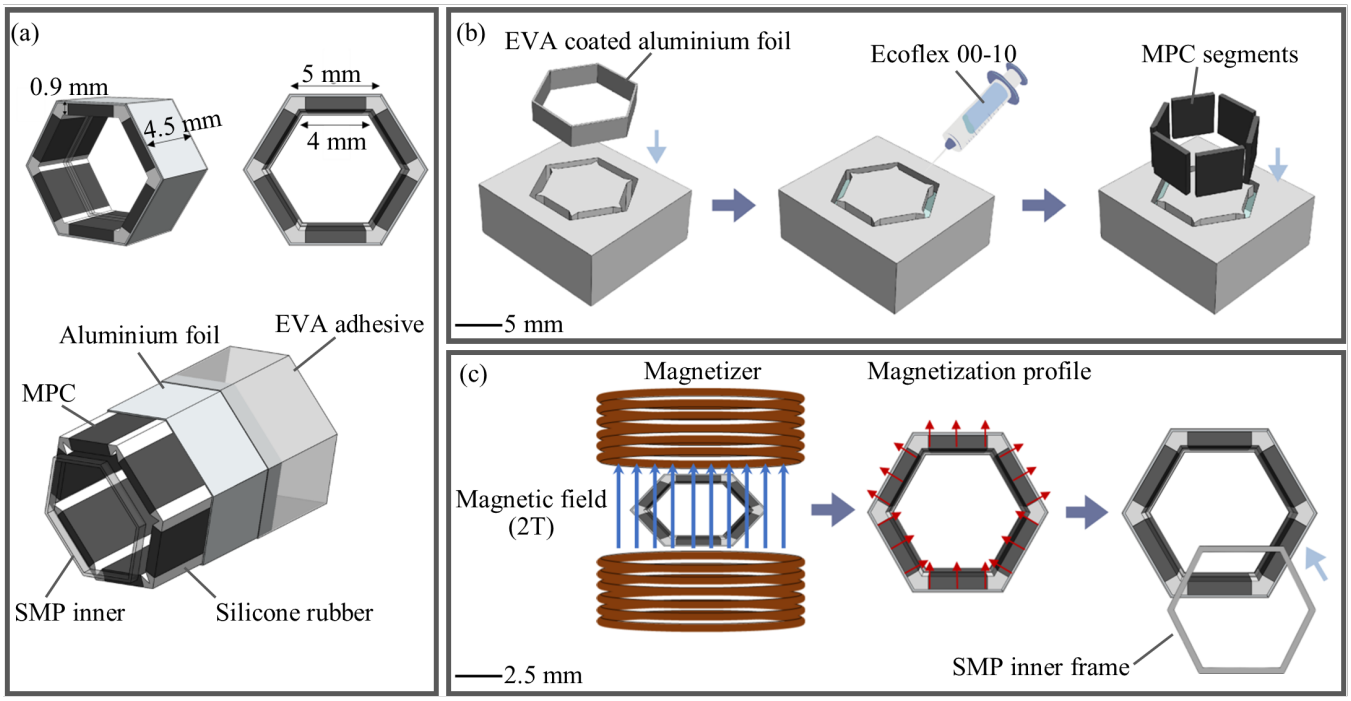


Fig. 2. Design and fabrication: (a) Components of hexagonal module, including material layers and dimensions (in mm). The structure consists of an outer layer of ethylene-vinyl acetate (EVA) adhesive for thermally reversible bonding, a layer of aluminum foil for radio frequency (RF) induced heating, a silicone rubber matrix with embedded magnetic particle composite (MPC) segments for actuation, and an inner frame made of shape memory polymer (SMP) for thermal shape fixation and recovery. (b) Fabrication steps: Placement of EVA-coated aluminum foil in the mold, followed by injection of Ecoflex 00-10 silicone and, finally, embedding of MPC segments. (c) Post-processing steps: Alignment of magnetic dipoles (red arrows) via exposure to a 2 T magnetic field (blue arrows) using external coils, followed by insertion and securing of the SMP frame inside the hexagonal module body.

However, the previous approaches using heat-activated bonding [15] and larger-scale magnetic assembly [16] present weak bonding forces between units, limiting structural integrity and preventing the swarm from maintaining stable assemblies. In this study, we introduce a modular magnetic soft robotic system composed of identical millimeter-scale hexagonal units (Fig. 1). The hexagonal geometry offers several advantages that make it uniquely suited for modular self-assembly. First, hexagons tessellate the plane without geometric gaps, allowing seamless edge-to-edge connectivity and structurally robust assemblies. Each unit provides six potential connection points, increasing versatility in forming chains or lattices. This geometry also distributes forces more evenly than squares or triangles, enhancing stability during locomotion [17][18]. The hexagonal modules can adapt to the environment and assemble into robust structures capable of overcoming obstacles that a single unit could not overcome. The assemblies perform cooperative tasks using a simple magnetic setup, without changes in unit design. Assemblies adapt to their environment by switching between two types of locomotion using magnetic fields. Each module integrates magnetically-responsive structures for locomotion and alignment, radio frequency (RF)-triggered components for localized thermal responses, and thermally tunable mechanical elements that adjust stiffness on demand.

We demonstrate that hexagonal modules exhibit maneuverability, self-assembly, and thermally responsive behavior through controlled experiments. When assembled, the modules display multiple locomotion modes and cooperative functional behaviors, expanding the range of tasks achievable through modular cooperation.

II. Design and Fabrication

In this section, we first present the structural design and functional layout of a hexagonal magnetic module. The rationale behind the layered configuration and component integration is described. Finally, the fabrication process is detailed.

A. Design

The system consists of magnetic soft hexagonal modules engineered for honeycomb-patterned assemblies, enabling functions that exceed those of individual units. Each module measures 5 mm in edge length, 0.9 mm in thickness, and 10 mm along its long diagonal. The dimensions are selected to ensure reliable small-scale fabrication while providing sufficient surface area for both magnetic coupling in assemblies and RF-induced localized heating required for bonding. The modules feature a multilayer structure designed to respond to both magnetic fields and thermal stimuli, triggered by RF and infrared (IR) light, respectively. The complete layered architecture of a hexagonal module is illustrated in Fig. 2(a). The outermost layer is an ethylene-vinyl acetate (EVA) adhesive that enables thermally reversible bonding between units [19]. Beneath it lies a thin aluminum foil that serves as a localized heating element. Under RF exposure, eddy currents

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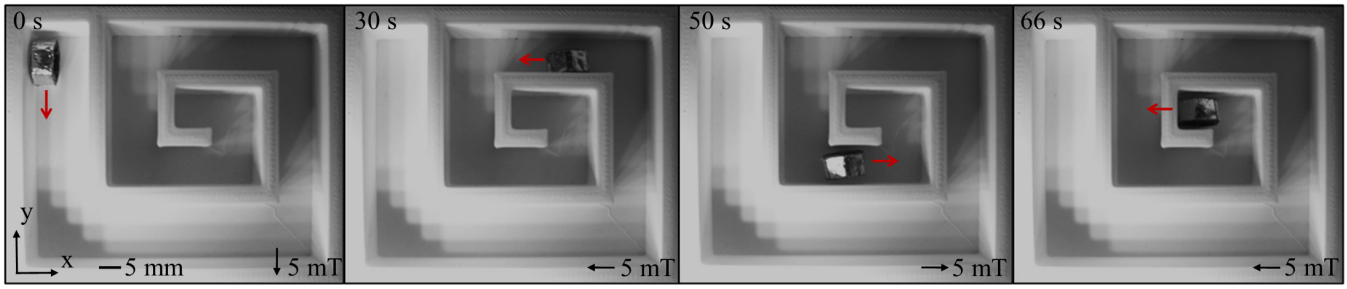


Fig. 3. Demonstration of the maneuverability of the hexagonal module within a maze (**0:05 in supplementary video**).

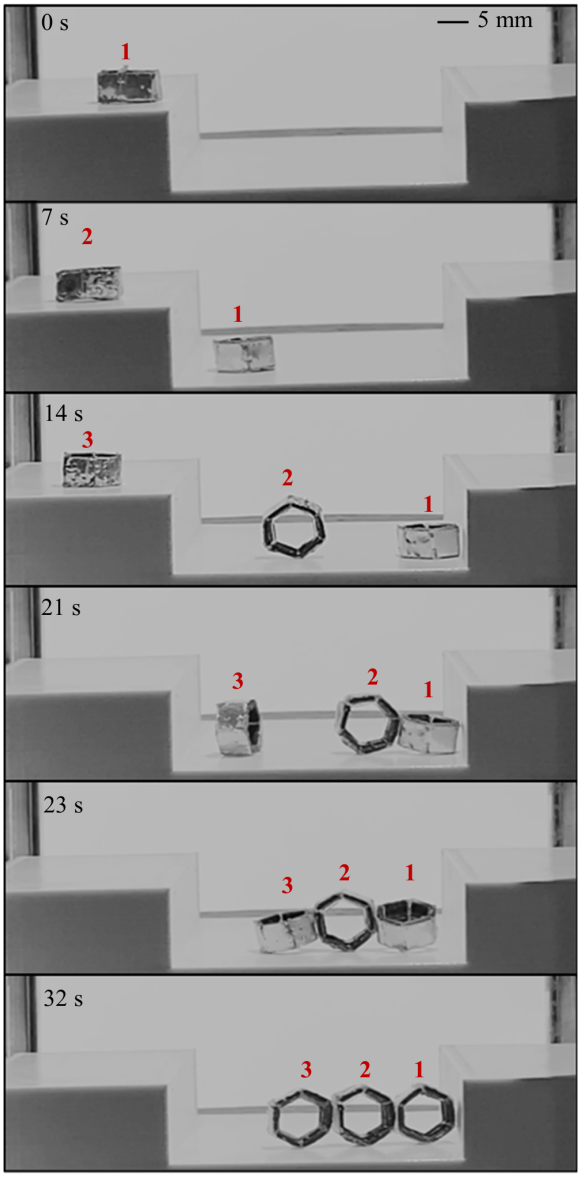


Fig. 4. Self-assembly of multiple hexagonal modules within a cavity. The modules sequentially enter the cavity, forming an organized structure (**0:14 in supplementary video**).

in the foil produce Joule heating, causing a rise in temperature [20], [21]. This localized heating activates the adhesive bonding mechanism on demand. The next layer is a silicone elastomer matrix embedded with magnetic particles, providing structural support and magnetic responsiveness. This layer is functionally divided, with stiffer magnetic–silicone composites along the hexagonal edges for actuation and softer silicone at the corners to allow controlled deformation. The innermost layer is a stiffness-variable frame made of shape memory polymer (SMP) that undergoes reversible shape changes when heated with IR light. Heating softens the frame, allowing the module to compress, while cooling restores rigidity to maintain the shape. Subsequent heating returns the frame to its initial configuration.

B. Materials and fabrication

Magnetic actuation is enabled through a magnetic polymer composite (MPC). The MPC segments consist of a silicone rubber matrix (Dragon Skin 30, Smooth-On Inc., USA) and ferromagnetic praseodymium-iron-boron (PrFeB) powder (MQFP-16-7-11277, Magnequench GmbH, Germany) with an average particle size of 5 μm and a maximum operating temperature of 80 - 120 °C [22]. Softer silicone rubber (Ecoflex 00-10, Smooth-On Inc., USA) joins the magnetic segments. RF responsiveness is achieved using a 15 μm thick aluminum foil. A UV-curable, biocompatible SMP (NOA63, Norland Products Inc., USA) provides temperature-dependent shape transformation capabilities [23], [24]. The fabrication process is illustrated in Fig. 2(b). A coated aluminum foil, with a thin layer of ethylene-vinyl acetate adhesive, is cut into rectangular sections (4.5×30 mm) and placed in a polylactic acid (PLA) mold with the adhesive side facing outward (Fig. 2(b)). Ecoflex 00-10 is injected to form the core structure, and pre-molded MPC segments are embedded in designated positions. The MPC is prepared using a 2:1 mass ratio of magnetic particles to Dragon Skin 30 and molded into segments (3.5×4.5×0.5 mm). After placing the magnetic segments in the mold, the structure is again degassed to eliminate trapped air, with additional Ecoflex 00-10 added if necessary for full bonding. Following demolding, the hexagonal module is compressed and exposed to a 2 T magnetic field to align magnetic dipoles. The SMP inner frame is cast using 3D-printed molds and secured with Ecoflex 00-10 inside the hexagonal module (Fig. 2(c)).

III. Results

This section is structured to transition from functional robotic demonstrations to the characterization of the oper-

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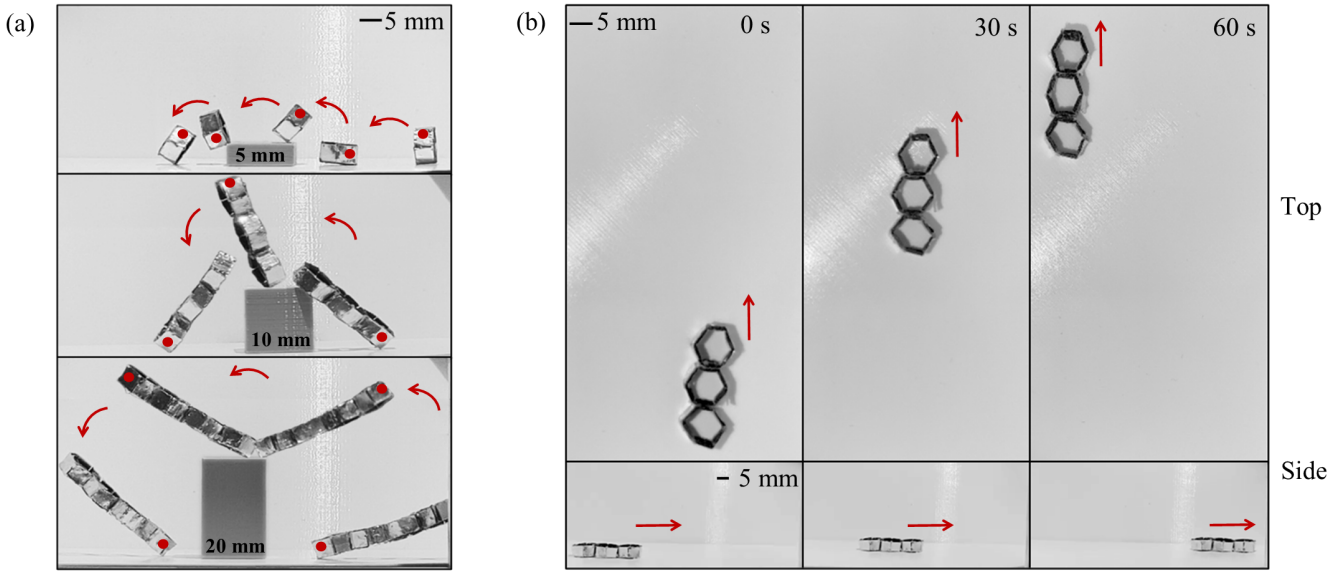


Fig. 5. Versatile locomotion of assemblies: (a) Modular assembly overcoming obstacles. The hexagonal modules can overcome obstacles of varying heights by forming assemblies (**0:25 in supplementary video**). (b) The hexagonal modules exhibit compression–extension locomotion. A 3×1 assembly progresses forward by alternating the strength of a uniform magnetic field, which drives rapid contraction and relaxation of the structure (**0:32 in supplementary video**). The strength of the magnetic field used for the contraction of the 3×1 assembly is 30 mT at a frequency of 2 Hz. Red dots and arrows indicate the direction of movement.

ational capabilities of the hexagonal modules. The study begins by showcasing the locomotion and self-assembly of a singular unit, subsequently expanding to modular assemblies joined via RF heating. These assemblies exhibit versatile movement modes, including compression–extension and tumbling, to navigate obstacles, as well as cooperative tasks where an assembly facilitates the traversal of a cavity by a separate module. This progression from individual to multi-unit behavior provides the necessary context for the subsequent thermomechanical characterization. Finally, the thermal response of the hexagonal module and the inter-unit bonding strength of the assembly are quantified to characterize the operational range of the modules.

A. *Maneuverability and self-assembly*

We use a three-axis Helmholtz coil system to evaluate the hexagonal module's maneuverability [8], [25]. The system generates uniform magnetic fields up to 50 mT within a 12×12×12 cm workspace. Directional control is possible along all three axes. The module is controlled via manual control of the magnetic field direction, while the magnetic field strength is predefined. The maze has a winding path that narrows from 12 mm at the edges to 7 mm at the center. This design tests the module's ability to navigate increasingly confined spaces. We guide the module from the periphery toward the center using 5 mT rotating magnetic fields (**0:05 in supplementary video**). Fig. 3 shows the module's movement and experimental results.

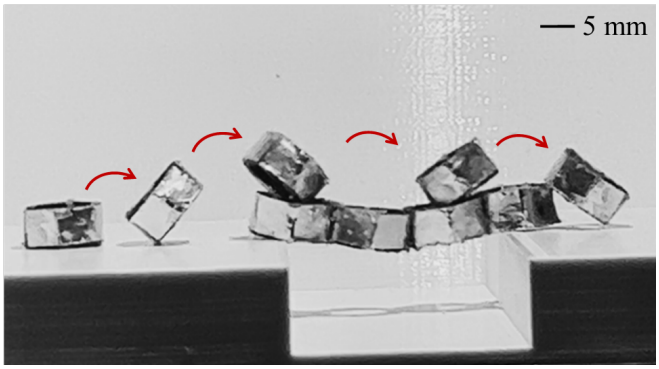


Fig. 6. Cooperative task. An assembly of hexagonal modules can serve as a bridge and assist an individual module in passing a cavity (**0:41 in supplementary video**). Red arrows indicate the direction of movement.

Individual maneuverability is essential for precise navigation. However, multiple modules working together achieve more complex tasks. After demonstrating locomotion, we explore how the hexagonal modules form assemblies in response to uniform magnetic fields. This behavior is driven by their programmed magnetization profile (see Fig. 2(c)), which enables passive alignment through remanent magnetic interactions. We evaluate this self-assembling capability by sequentially introducing three modules into a 15 mm deep 3D-printed cavity and actuating them using a two-axis Helmholtz coil system [26]. A 5 mT rotating magnetic field is applied during this process, causing each new module to slightly displace the previously placed ones while remaining confined. After the third module enters, a unidirectional magnetic field prompts the modules to align according to their magnetization. This results in a stable 3×1 assembly, showing the transition from individual movement to organized, collective behavior. Fig. 4 presents the experimental procedure and results (**0:14 supplementary video**).

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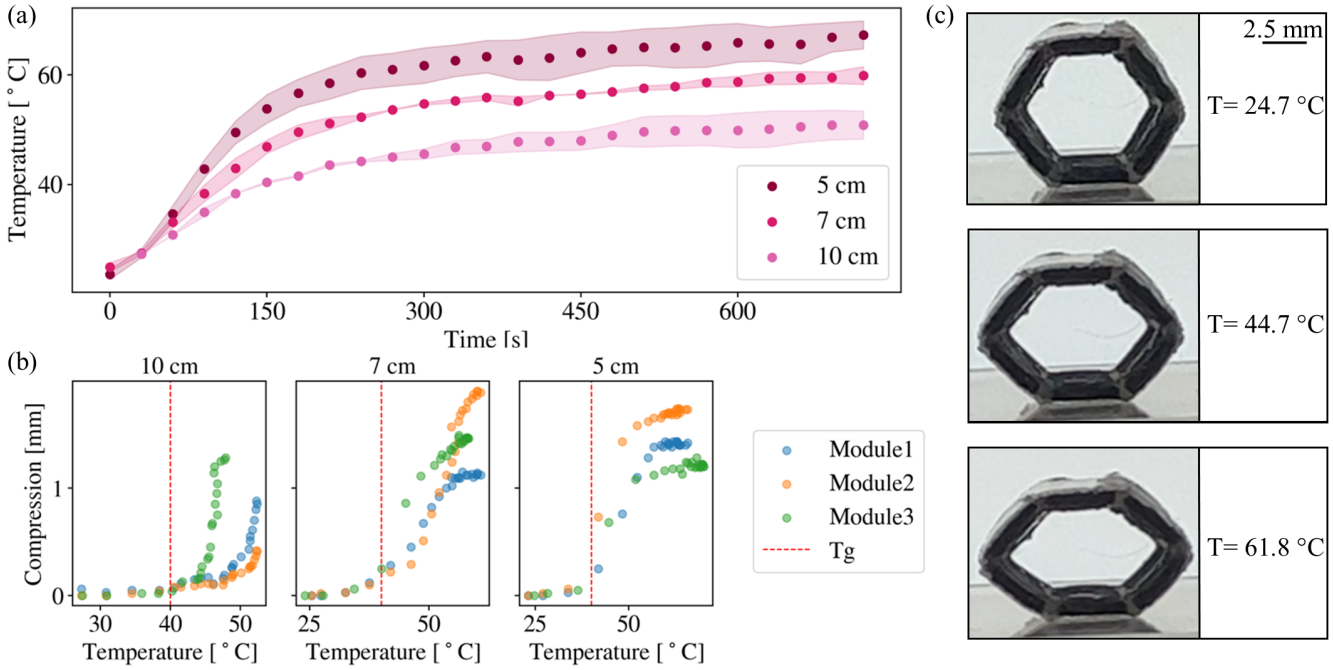


Fig. 7. Thermal response characterization of hexagonal modules: (a) Temperatures achieved by a hexagonal module in 720 seconds at 5 cm, 7 cm and 10 cm away from the IR source. (b) Compression of a hexagonal modules at 5 cm, 7 cm and 10 cm from the infrared (IR) source and under the influence of a 5 mT magnetic field. Red line represents the glass transition temperature of the SMP frame. (c) Hexagonal unit compressing under the influence of a 5 mT magnetic field at 24.7 °C, 44.7 °C and 61.8°C (**0:50 in supplementary video**).

B. Functions of assemblies

We evaluate the functional capabilities of bonded assemblies through three experiments focused on collective and cooperative behavior. Assemblies form using programmed magnetization profiles and RF heating, which increases stiffness at contact points. The experiments include obstacle-crossing tests at heights of 5 mm, 10 mm and 20 mm. Deformation-based locomotion is tested using a linearly bonded 3×1 assembly. A cooperative task is also performed, where a bonded 4×1 structure acts as a passive bridge for a separate untethered hexagonal module.

The bonded assembly successfully traverses obstacles up to 20 mm, which is twice the length of the module's long diagonal. This indicates that RF-induced stiffness is sufficient to maintain structural integrity during locomotion over uneven terrain (Fig. 5(a)). In the deformation-based experiment, the 3×1 assembly moves forward by repeating a compression and expansion cycle. It compresses when the magnetic field reaches 30 mT and expands as the field drops to 0 mT. The SMP frame is omitted due to heating limitations (Fig. 5(b)).

For the cooperative task, a 4×1 bonded assembly is manually positioned across a 25 mm gap, while a single hexagonal module is placed nearby. When a 5 mT rotating magnetic field is applied, the bonded structure remains stationary, acting as a stable bridge. Meanwhile, the individual module tumbles over the assembly to successfully traverse the 25 mm gap (Fig. 6). The difference in behavior arises from mass and frictional forces. Although the single module and the assembly experience similar magnetic torque, the assembly remains stationary. The assembly has a greater mass and larger contact area with the surface than a single module, which prevents motion.

C. Characterization of hexagonal modules

In this subsection, we first evaluate the thermally responsive behaviour of the SMP frame of the hexagonal modules. The SMP frame forms the innermost layer of the hexagonal module and acts as a variable-stiffness skeleton. We evaluate the module's thermally induced mechanical response under an external magnetic field to determine the achievable degree of compression. This transition is critical

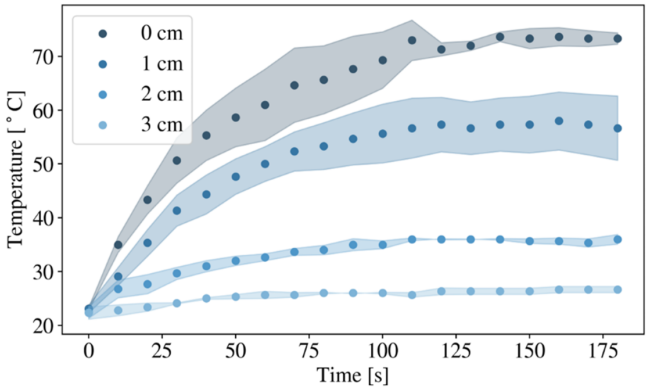


Fig. 8. Temperatures achieved by a hexagonal module by RF heating at 0 cm, 1 cm, 2 cm and 3 cm away from the center of the RF coils. Triplicates.

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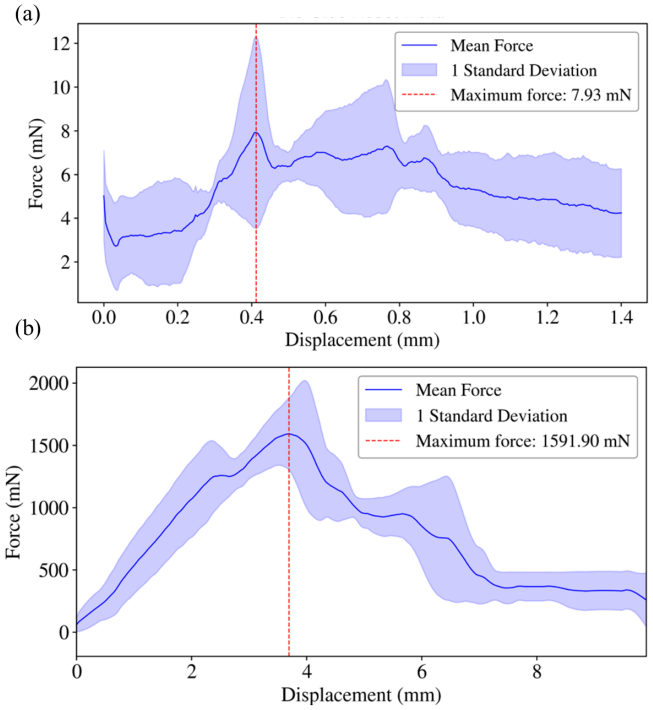


Fig. 9. Tensile testing of modular assemblies. (a) Tensile force needed to separate an assembly of two hexagonal modules hold together by remanent magnetic fields. (b) Tensile force needed to separate an assembly of two hexagonal modules hold together by ethylene-vinyl acetate adhesive bonding. Three samples were tested. Sampling frequency of 53 samples/second.

for locomotion: at low temperatures, the rigid SMP frame maintains the module's shape for stable tumbling, whereas at higher temperatures, the frame softens to allow magnetic-field-induced compression and extension.

Controlled heating is applied using an IR radiation lamp (Deep Heat Projector, 80 W, Arcadia) positioned at 5 cm, 7 cm, and 10 cm above the module. A neodymium permanent magnet (NdFeB, R750F, Amazing Magnetic LLC, California, U.S.A) is placed beneath the module. The magnet generates a field of 5 mT at the base of the module. This field interacts with the module's programmed magnetization. As a result, the module compresses vertically (**0:50 in supplementary video**). Temperature changes are monitored using a thermal imaging camera (ThermoVisualizer Pocket, Laserliner, Arnsberg, Germany).

The module deforms under magnetic force only when the SMP exceeds its glass transition temperature (T_g) of 40°C. At this point, the polymer transitions from a rigid, brittle state to a flexible, rubbery form, allowing controlled compression [27], [24]. Maximum temperatures reached at different IR distances are shown in Fig. 7(a). Corresponding compression behavior under the magnetic field is illustrated in Fig. 7(b), where the red dotted line marks the T_g, respectively Fig. 7(c). These results highlight the SMP's critical role in enabling temperature-dependent, reversible shape transformations.

In addition to IR heating for locomotion, we assess the module's response to RF fields to characterize the thermal activation of the bonding mechanism. RF heating is utilized to target the aluminum foil layers, which in turn melt the EVA adhesive. This process is essential for cooperative behavior, as the melting of the EVA adhesive enables the bonding of adjacent modules. We evaluate the module's thermal response to RF fields by placing it at 0 cm, 1 cm, 2 cm, and 3 cm from the RF coil center. The RF system generates a 125 kHz field at 20 W. Results in Fig. 8 show a maximum temperature of 74°C at 0 cm. Temperature decreases with distance, reaching a minimum temperature of 27°C at 3 cm.

A tensile test evaluates the effect of EVA adhesive on the strength of modular assemblies to quantify the mechanical robustness of the modular assemblies. The mechanical robustness of the assemblies directly dictates the system's cooperative capabilities. Fig. 9 compares assemblies held together by remanent magnetization versus RF-heated EVA bonding. Adhesive bonding increases the maximum tensile force by 200 times (7.9 mN vs 1.6 N), greatly improving mechanical robustness. For magnetically assembled modules, the persistent force after the peak remains below 10 mN, likely due to residual magnetic attraction. In EVA-bonded assemblies, the post-break tensile force suggests incomplete adhesive failure. Other components, such as silicone rubber or aluminum foil, fail before the melted EVA fully separates.

IV. Discussion

The results show that hexagonal modules can navigate paths as narrow as 1.5× their diameter using a 5 mT rotating magnetic field, demonstrating precise maneuverability in confined spaces. Modules self-assemble through programmed magnetization, forming scalable modular architectures. Multi-axis magnetic control or dynamic field modulation could improve stability and repeatability.

RF heating of EVA adhesive at 70–74°C enabled strong bonding. Bonded assemblies in the present work are approximately 200× stronger than magnetically held modules, with a maximum bond force of 1.6 N. By comparison, previous studies reported maximum bond strengths of around 250 mN for thermally bonded units [15] and 25 μN for magnetically bonded units [16].

The stronger bonds in our assemblies enable the system to overcome obstacles up to 20 mm, which individual modules were unable to surmount. From a geometric perspective, the maximum surmountable height is fundamentally determined by the cumulative vertical reach of the assembly. Since each hexagonal unit has a height of 8.5 mm, an N-unit assembly provides a proportional increase in structural length; for instance, a 3×1 assembly reaches 25.5 mm, while a 4×1 assembly reaches 34 mm. Our experimental observations indicate that successful navigation depends on the assembly being taller than the obstacle, providing the necessary clearance for the units to 'step' over the barrier together. While it is not yet certain how much lower the obstacle height must be compared to the theoretical upper limit for guaranteed traversal, these results provide a clear proof-of-concept for the height advantages of cooperative assemblies. Currently, the scalability of these assemblies is limited by

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the workspace of the Helmholtz coil magnetic system. While theoretical modelling of obstacle surmounting, such as predicting the maximum obstacle height for a given number of units by evaluating the morphological computation and structural compliance of the assembly, would provide further insights, the present study focuses on experimental validation of the multi-responsive soft unit design. Detailed modelling and performance prediction will be addressed in future work as part of extending this proof-of-concept study.

Furthermore, due to these spatial constraints of the magnetic workspace (specifically within the Helmholtz coils), a complete, continuous workflow integrating self-assembly, RF bonding, and subsequent cooperative locomotion has not yet been presented. The physical bounds of the Helmholtz workspace restricted our ability to simultaneously integrate the RF coils required for localized heating during EVA bonding, as well as the IR heating setup necessary to trigger the switchable compliance of the SMP frame for compression-based locomotion (Fig. 5(b)).

A 4×1 bonded assembly acted as a passive bridge for a single module to cross a 25 mm gap. The module can traverse a cavity of arbitrary length, provided that the assembly length exceeds the cavity span and is formed by two or more units. Experimental results indicate that a single module can move under a 5 mT magnetic field. However, assemblies consisting of two or more modules require field strengths greater than 5 mT to generate sufficient magnetic torque to overcome gravity and friction, and thus remain stationary under 5 mT. The reduced mobility of assemblies arises primarily from increased mass, which enhances the normal force and thus frictional resistance. Consequently, assemblies remain stationary under magnetic torques that are sufficient to move individual modules. Adjusting module size, contact area, or adhesive placement could fine-tune such task-specific behaviors. These results show that assembled structures perform tasks beyond individual modules, including overcoming large obstacles, enabling different locomotion strategies, and supporting other modules in cooperative scenarios.

Beyond these structural roles, the variable stiffness of the SMP frame can add substantial functional value to the soft robot, particularly for targeted cargo delivery. The SMP frame can offer stiffness-modulated delivery of liquids encapsulated within soft membranes. During cargo transport, the rigid SMP frame serves as a passive protector to safeguard the liquid-encapsulated sample. Upon arrival at the target destination, localized heating softens the SMP frame, allowing the soft robot to compress under magnetic actuation so that the capsule ruptures and the liquid is delivered. This localized thermal activation is highly advantageous for multi-cargo assemblies, as different types of liquids can be transported simultaneously within a single structure, while allowing only the specifically targeted modules to soften and release their encapsulated samples.

Thermal characterization using IR and RF heating revealed spatial constraints. Maximum temperatures occurred near the energy source and decreased with distance. This data is provided to characterize the operational range of the modules and to show how the heating source must be positioned to achieve the desired mechanical response and inter-unit bonding. As shown in Fig. 7(b), compression values differ at identical mean temperatures depending on distance. This is due to the Inverse Square Law, $I \propto \frac{1}{d^2}$, where reducing the distance from 10 cm to 5 cm quadruples the radiant flux density [28][29]. This higher intensity is reflected in the significantly steeper heating rate (dT/dt) for the 5 cm setup in Fig.7(a). This high-energy environment establishes a pronounced thermal gradient, causing the outer surfaces of the module to reach the glass transition temperature (T_g) more rapidly than the interior [29]. As these external layers transit to a compliant 'rubbery' state [30], the resulting localized softening allows the 5 mT magnetic field to trigger compression even when the measured average temperature is lower. SMP frames exhibited temperature-dependent flexibility, enabling reversible and controllable deformations. Optimizing heat delivery and module placement could improve actuation efficiency.

V. Conclusions and Future Work

In this work, we present a modular, untethered platform composed of magnetically-actuated hexagonal units. The modules self-assemble into functional configurations for versatile and cooperative tasks. The platform combines magnetically-responsive composites, RF-triggered bonding, and thermally tunable stiffness to achieve maneuverability and scalable assembly.

The results demonstrate that the modular hexagonal unit combines maneuverability with collective and cooperative capabilities. Individual modules successfully navigate confined spaces, while bonded assemblies perform tasks beyond the reach of single units, such as crossing obstacles up to 20 mm, twice the long diagonal of a module. Thermal activation through RF-induced heating reaches 74°C at the coil center, enabling strong EVA bonding. This bonding increases tensile strength by $200\times$. These results highlight the potential of combining magnetic and thermal strategies for reconfigurable, mechanically robust modular platforms.

Despite demonstrating functional and mechanical advances, the modular magnetic soft robotic system still faces several challenges. While the current work focuses on linear cooperation, extending the system to two-dimensional (2D) grids would provide a more stable platform for the transport of larger objects. Beyond 2D, the interaction between multiple modular layers could lead to three-dimensional (3D) assemblies capable of encapsulating cargo for secure transport or creating protective housings.

However, transitioning to 2D and 3D configurations introduces clear technical limitations. The most significant is thermal interference, where the heat required to soften one module may unintentionally affect adjacent units in a dense grid or stack. Additionally, magnetic coordination becomes more difficult as the number of neighbouring units increases, which can lead to alignment errors during assembly. Addressing these thermal and magnetic constraints is essential

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for transitioning from individual modules to more complex, multi-layered robotic systems.

To address these challenges and expand the utility of the platform, future work will also focus on physical scaling and structural reversibility. First, the hexagonal units could be scaled down to smaller sizes in future iterations. While this downsizing approach may introduce fabrication difficulties due to the complex, layered design of the soft robot, necessitating the investigation of alternative fabrication techniques, it also offers major physical benefits. Because the locomotion of the hexagonal modules developed here is driven solely by magnetic torques, operating at smaller scales increases actuation performance. Under the same external magnetic field, magnetic torque demonstrates higher efficiency than magnetic force at small scales. This is because magnetic force scales with the volume of the magnetic material (proportional to L^3), whereas the equivalent force generated by magnetic torque scales with the area (proportional to L^2) [31].

Second, a reliable disassembly strategy must be formulated to achieve fully reversible modularity. We hypothesize that re-heating the bonded interface will lower the viscosity of the EVA adhesive, thereby significantly reducing its bonding strength. While the adhesive is in this melted, low-viscosity state, applying magnetic actuation to initiate a tumbling movement is expected to generate sufficient torque to overcome the weakened bond and detach the modules, allowing the modular assembly to successfully disassemble.

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