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MagBot: Reconfigurable Modular Soft Pneumatic Actuators with Tunable Magnetic Connection Mechanism

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Abstract— **Soft robots are growing in demand due to their inherent soft nature, compliance, and versatility. These attributes make them ideal for a large range of applications. To further expand the applications of soft robotics, we present a reconfigurable modular soft robotic actuator capable of easy reconfigurations and multi-actuator assembly for versatile tasks using a single actuator design. In this paper, we introduce a novel inter-unit connection mechanism that expands the reconfiguration capabilities of our soft modular robots. The mechanism includes magnets that can semi-permanently reverse their polarity on demand to achieve tunable magnetic connections without the need to supply constant electric current. The mechanism is made from a flexible material allowing articulated connections, which enables complex spatial configuration in a multi-actuator assembly. In addition, the mechanism allows various inter-unit connections, including air, mechanical, and electrical, that reduce the complexity of operation and reconfigurability. These connections enable a multi-actuator assembly to share a single actuation source, that simplifies the design and increases the functionality. We characterize the mechanical performance of individual actuators and the connection mechanism through experiments. Examples of structural configurations are presented to demonstrate the actuators' reconfiguration capabilities.**

I. Introduction

Soft robots have revolutionized the way we think about robotics. Soft robots are often nature-inspired and offer methods of grasping and locomotion beyond the traditional robot design [1]. Introducing degrees of modularity to these soft robots opens new opportunities for advanced functionalities of modular robots, commonly made from a single actuator design [2]. The use of modular robotic actuators allows for a single robotic design to be used in a large range of applications, including manufacturing, medical device, entertainment, and search and rescue [3]. However, current soft robotic systems are predominantly designed for specific tasks, lacking the adaptability to change morphology and perform versatile tasks on-demand. Overcoming this challenge involves the development of a novel modular, reconfigurable soft robotic actuator capable of swift and versatile morphology changes, thereby enhancing operational capabilities.

Most existing modular soft robots consist of simple, elemental, soft actuating modules connected to one another via rigid components. The size of these modules can vary greatly, being as small as a centimeter to reaching up to a meter-scale [4], [5]. In all cases, the versatility of these

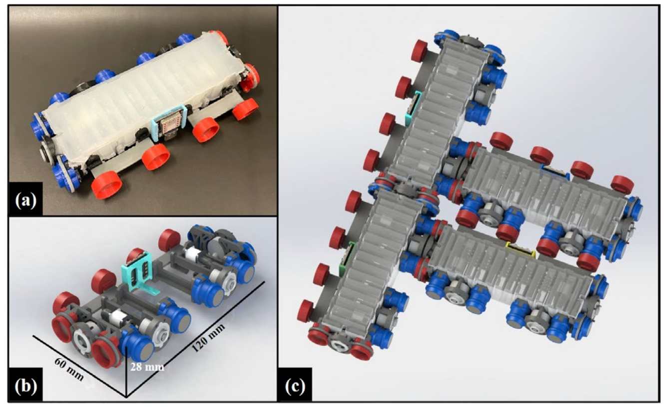

Figure 1. a) Elemental modular actuator. b) Dimensioned CAD view of the modular actuator with the soft silicone component removed, showing internal support structure. c) Examples of inter-unit connections.

modular systems has been shown to increase both the functionality and functions of these robotics systems in different working environments. The use of a modular design allows for a single robotic system to replace multiple task-specific robots, improving productivity and reducing the cost of operation.

There exist multiple methods of connectivity in between modules. An ideal modular robotic system needs to be simple and quick to disconnect and connect, where the connection can be either controlled or autonomous. The most used connectivity mechanisms utilize mechanical, magnetic, adhesive, and vacuum principles [3]. Among these, the magnetic mechanism is an attractive option as it is simple and reversible. This mechanism allows for actively controlled interconnection of modules utilizing either permanent magnets with predefined magnetic fields [6], electropermanent magnets (EPM) that allow tunable connectivity based on the applied electric current [7], or magnetic soft composites with pre-programmable magnetization [8]. The existing modular actuators that utilize these magnetic connection mechanisms are capable of versatile locomotion, grasping, and structural reconfiguration capabilities with a single elemental design [9]–[11].

Here, we introduce a modular soft pneumatically driven actuator featuring a unique inter-unit connecting mechanism, facilitating versatile connections between actuators in various configurations (see Fig. 1). The design incorporates connectors on all sides of the actuator, allowing for end-to-end, side-to-side, or end-to-side connections. Its flexible side connections enable articulated connections for forming spatial robotic configurations. Moreover, this connector design integrates a centralized system for air supply, power, and signal communication, enhancing the potential for

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autonomous structural optimization and self-reconfigurability through individual microcontrollers. Additionally, the connectors utilize a novel tunable magnetic mechanism inspired by electropermanent magnets [12], enabling direction-controlled connections without constant electric current supply, thus conserving energy, and enabling variable attractive or repulsive forces between units. These advancements in connectivity, energy efficiency, and articulation significantly enhance the autonomy and spatial structural adaptability of modular soft robots, broadening their potential applications.

The actuator presented herein is developed based upon our initial work reported in [13]. The proposed actuator was completely redesigned and includes several advantages. Contrary to using permanent magnets with coils, we use magnets whose polarity can be reversed, which significantly reduced the amount of power needed for connections. The mass of the actuator was reduced due to fewer rigid parts, which increases the actuator's force-to-weight ratio. The connectors are made of flexible material that replaced rigid hinges. Importantly, the new miniature connectors allow for pneumatic, mechanical, and electronic connections between units, which enables having a single power source and easy communications between units. These improvements significantly simplified the actuator design and enhanced its functionality.

In the remainder of this paper, we first present the design and fabrication of the elemental actuators. Next, we discuss the experimental results of characterizing the mechanical performance of the soft actuator and reversible magnet-based connectors. Following, we present various planar and spatial structural configurations to demonstrate their reconfiguration capabilities. Last, we summarize our findings and discuss potential future directions.

II. Design and Fabrication

A. Elemental Unit

The design of these modular pneumatic units (MPUs) starts with choosing the overall dimensions as 120 mm in length, 60 mm in width, and ~30 mm in thickness (Fig. 1b). The magnets are spaced out in multiples of 30 mm to allow the units to be reconfigured in multiple ways and allow for scalability of robotic configurations. A single unit includes connections on all four sides of the individual actuator, enabling the actuators to interconnect end-to-end, side-to-side, or end-to-side (Fig. 1c). Each MPU has one end and one side that consist of reversible magnets with coils (RMCs) (identified by the blue plastic housings). RMCs are used to engage and disengage the connection between units autonomously (without physical human interaction). On the opposite side of RMCs are hinges that allow articulated connections, enabling the formation of spatial robot configurations. These hinges are constructed using a flexible thermoplastic, polyurethane (TPU), and are attached to a rigid plastic housing (indicated in red) that holds the permanent receiving magnet of the magnetic connection between units (Fig. 2a).

The magnet and magnet receiver pieces consist of a concave shape and a convex shape. This aids in the alignment

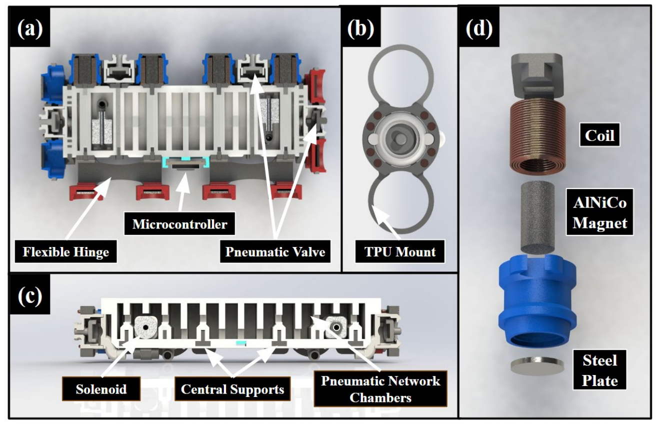

Figure 2. a) Top-down cross-sectional view of the actuator. b) PAC connector and soft mounting TPU component. c) Side, cross-sectional view of actuator. c) Exploded view of RMCs showing the plastic casing, AlNiCo magnet, steel plate, and wire coil.

of the connections as well as locking the units in place when engaged. The end housings are "soft mounted" using a flexible TPU material. This is done by securing the end magnet casings to the power, air pressure, and communication (PAC) connector via a 3D printed flexible part (Fig. 2b). This adds another degree of flexibility to the actuator by allowing the end connectors to expand and flex to accommodate expansions when the soft actuator is inflated and bends.

The RMC design is inspired by electropermanent magnets [1], [2]. RMCs consist of an AlNiCo (Aluminum Nickel Cobalt) magnet whose polarity can be semi-permanently reversed by inducing a strong enough magnetic field in the opposing direction. For these magnetic connections, rather than cancelling out the magnetic field of permanent magnets in EPMs by inducing an electric current, the RMCs are designed to reverse the magnet polarity, causing the RMC to separate from the receiving magnet. This semi-permanent approach minimizes energy consumption while achieving tunable inter-unit connectivity through variable attractive or repulsive forces. The RMCs are constructed by wrapping 26-gauge wire around a 6.4 mm in diameter and 6.4 mm thick AlNiCo magnet. This magnet with coil is placed in a plastic housing and mounted to the internal central support structure of the pneumatic actuator (Fig. 2d).

B. Power, Air, and Communication

To increase the functionality and reduce the complexity of the MPUs, a centralized connector was designed to allow for shared power, air pressure, and communication (PAC connector) between all units (Fig. 3). The electrical connector requires 4 pins for power and signal to be shared. The connector's female side (Fig. 2b) features 4 mirrored pin-receiving-contact-surfaces on the top and bottom to allow for reversal of the inter-unit connection [14]. These are spring-loaded pogo pins that are 1.5 mm in diameter and 6 mm in length (Fig. 3a). The center of each PAC connector is a 3D printed miniature air valve that consists of multiple O-rings and springs (Fig. 3b). When the units engage, the two valves are opened via the internal pins and air is allowed to pass through both units (Fig. 3d-e).

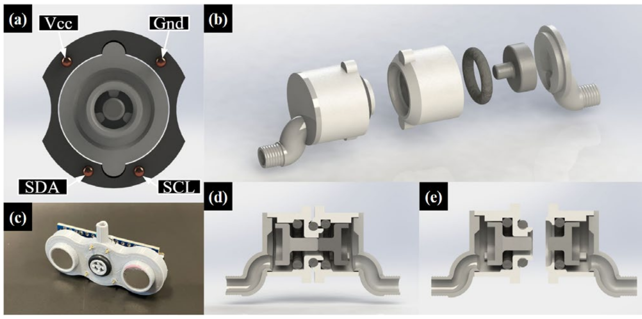

Figure 3. PAC connector. a) Front view with indicated spring-loaded pogo pins for electrical connections. b) Exploded view of a PAC connector showing valves, housing, and O-ring. c) Input module in a housing with a master control board for communication and PAC connection for main power and air input (air supply tubes and wires not shown). d) Open and e) closed state of a custom, miniature pneumatic valve.

All the wiring is routed throughout the actuator using a flexible PCB board. Power and communication are connected in parallel. The control of the transistors for powering RMCs and solenoid valves is done on the PCB board. The board lies flush with the bottom of the pneumatic actuator, close to the bending axis where the inextensible layer is located.

C. Pneumatic Actuator Molding

The designed soft, pneumatically driven actuator module is constructed of a flexible silicone rubber. The modules are based off a pneumatic network, which consists of multiple chambers that are inflated with positive air pressure. Modules are made of Dragon Skin 10 (Smooth-On, Inc., Macungie, PA) silicone rubber. The structure of the internal pneumatic network is complex due to the added rigid components that support PAC and RMC connectors. A multi-part mold is required for fabrication consisting of an upper mold, a lower mold, end caps, and support place holders (Fig. 4).

The upper mold and inserts create the pneumatic network chambers and internal channels. The lower mold creates the bottom of the MPU and an inextensible, fiberglass mesh is embedded inside. The end cap molds prevent the silicone rubber from flowing out while also holding the plastic-to-silicone interface that attaches the hard magnet casings to the soft actuator. The center support place holders are added to the bottom mold and allow for supports to be placed through the silicone actuator later during the assembly process.

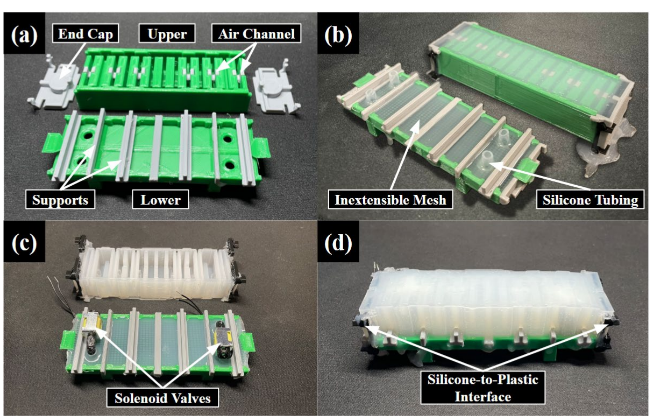

Figure 4. Molding of the pneumatic actuator. a) 3D printed mold pieces for fabricating the actuator. b) Pouring silicone rubber into the molds to create upper and lower sections of the pneumatic network. c) Placement of solenoids with attached 3D printed fittings through silicone tubes of bottom mold. d) Final step of molding process, where top and bottom sections are glued together with additional silicone rubber.

The silicone rubber is mixed in a graduated plastic cup and placed into a vacuum chamber to remove any air bubbles that have been incorporated into the mixture during mixing. The particular silicone used has a pot life of 30 minutes and cures in 4 hours. Once the upper and lower molds have been cured and before they are assembled, two two-way micro solenoids are placed inside the chambers of the actuator and a small silicone tube is placed through the bottom of the unit, allowing the MPUs to control their air pressure internally rather than utilizing an external control valve (Fig. 4c).

D. Communication and Control

The units are controlled via a two-wire I^{2}C communication protocol. Each unit is coded as a slave, awaiting commands from a master controller. Each unit is given an identifier number and once attached to the inter-unit network, the master microcontroller sends commands and information to the units, including how much to inflate or which magnets to engage/disengage. Acting as the master controller is a separate input module (Fig. 3c), which also supplies air pressure and power to all the units via the PAC connector. This centralized input module simplifies the reconfiguration process of these actuators, allowing one to add multiple units to the system without additional programming and connections.

III. Results

A. Mechanical Performance of the MPAs

The individual pneumatic actuators and RMCs were tested to determine their mechanical performance and capabilities. The bending test was performed to show the pneumatic actuators' abilities to bend and correlate air pressure to bending angle. The hard components embedded in the actuator design did not hinder its ability to bend. The results showed that the actuator could bend up to 200 degrees at 6 psi (Fig. 5a). The bending angle shows nonlinear trend with respect to the inflation pressure that is due to the inherent nonlinear properties of the silicone rubber. Rapid

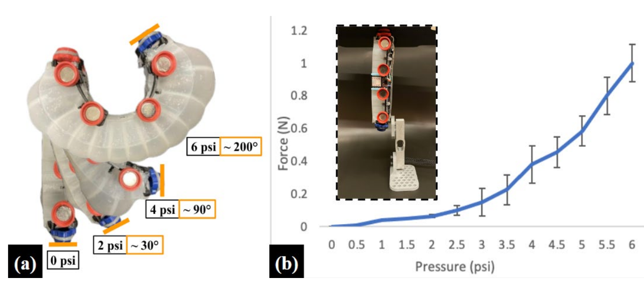

Figure 5. a) Visualization of the correlation between air pressure and angle of actuation. b) Blocked force data of a single actuator, showing the relationship between air pressure and produced force. Embedded image shows setup for recording blocked force data.

changes in bending angle are observed at inflation pressure approaching 6 psi.

The strength of the actuator was defined as its force-to-pressure ratio. A digital load cell (1 kg Strain Gauge, Adafruit, New York City, NY) was calibrated and used to measure the blocked force of the actuator in respect to the supplied air pressure used for actuation; see Fig. 5b. This ratio was found to be approximately 0.31 N/psi, which was calculated from the average slope between 3-6 psi. The actuator exhibits higher strength compared to other similar pneumatic actuators (0.1338 N/psi) [15].

B. Characterization of Reversible Magnets with Coils

The RMCs utilize the AlNiCo magnet's ability to flip its magnetism when introduced to a strong enough opposing magnetic field. Due to the inherent small nature of the MPU design, the coils needed to be able to fit within the small housing while still having the capability of reversing the polarity of the magnet. To determine which wire gauge was best to use, various wire thicknesses were tested to optimize the RMC design. The thinner the wire, the greater the number of windings of coils can be produced. This means higher voltage requirements but lower current load. Four wire thicknesses (24, 26, 28, and 30 gauge), were wrapped around 6.4 mm diameter AlNiCo magnets. The coils each had a maximum outer diameter of 11 mm to fit within the RMC housing. Each of these coils were supplied with 4 fixed voltages (i.e., 4, 8, 12, and 16 V), each with unrestricted current flow enabled by the use of a lithium-ion battery. Fig. 6 shows the measured results of the magnetic field strength produced at the tip of the magnet. The 26-gauge wire at a voltage of 12 V was determined as the optimal combination to power the RMCs as it produced sufficient magnetic field to cancel out the magnet's own field and was sufficient to flip the magnet polarity. The use of the 26-gauge wire was chosen over 24 gauge to minimize power and increase safety, as less current is required to power the RMC.

The resistance for each coil was measured and recorded to determine the estimated current draw and length of magnet wire used (see Table 1 in the Appendix). Using the measured ohms and the known resistance of each wire gauge per meter, we estimated the length of the wire needed to produce the

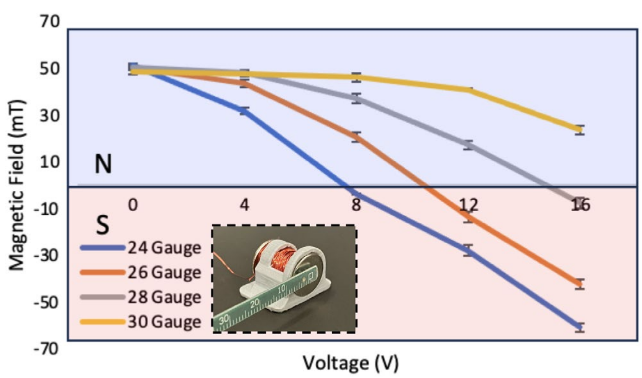

Figure 6. Reversible magnet with coil testing results. The graph represents the magnetic field of four trials with varying wire diameters and voltages. Each test was repeated two times. The magnetic field strength was measured at the tip of the magnet, as seen in the embedded image.

coil. To create RMCs that have consistent properties and operation, the length of wire needed for each coil can be measured before winding. In determining which wire size to choose, we considered safety of operation and power consumption by investigating required voltage and current running through the coils. Using the measured resistance and Ohms Law's (Voltage = Current × Resistance), a calculated current draw is found for each voltage input (see Table 1 in the Appendix). The 26-gauge wire was found to draw about half as much current as 24-gauge wire, requiring 26 amps. Assuming equal duration, this requires significantly less energy, and thus is the preferred option. While the current draw is high, the RMCs require only momentary power draw (~100 msec), making them a power efficient alternative to the electromagnets. Once the RMCs are polarized, they act as permanent magnets in passive mode and do not require power for their operation.

C. Reconfigurability of MPAs

The flexible connections allow the MPAs to be arranged in a novel way compared to the other existing similar soft robots. There are three main connection types that can be classified: end-to-side (Fig. 7a, e), side-to-side (Fig. 7b, c), and end-to-end (Fig. 7d). Side-to-side connections utilize the four side connectors, including the hinge component of the MPAs. These hinges allow the units to bend greater than 90 degrees along their width while maintaining a strong connection. This is a useful and important characteristic as it allows the MPAs to form spatial configurations (Fig. 7c, e).

End-to-end connections allow the MPAs to form linear-based structures (Fig. 7d). These structures could be used for grasping applications or behave similarly as a wrist in a hand-like structure. Side-to-end connections can be used as the digits in the same hand-like structure, allowing this robotic configuration to grasp objects of various sizes with greater dexterity.

It's worth emphasizing that while this design doesn't currently feature complete self-reconfiguration capabilities, incorporating reversible magnets lays the groundwork for achieving full reconfigurability in the future. As this design evolves and advances, the potential for seamless adjustments will be enabled by developing control algorithms for self-reconfigurability. Despite the facts that all the showcased configurations stem from manual manipulation, the proposed robot demonstrates the versatility and adaptability inherent in the modular units.

IV. Discussion

There are a few concerns with the design that may affect its usefulness as an actuator. The important one is the increased complexity of these actuators when compared to other similar actuators and soft robots. With the introduction of microcontrollers and onboard solenoids, while they are very capable, they might not be best suited for all working environments. However, because of the increased complexity of the soft actuators, the MPAs are capable of being tethered to a single point rather than supplying air and power to each individual unit. This could improve its functionality and usefulness in situations where air hoses and wiring could cause an issue (such as tight/narrow spaces) and reduce the

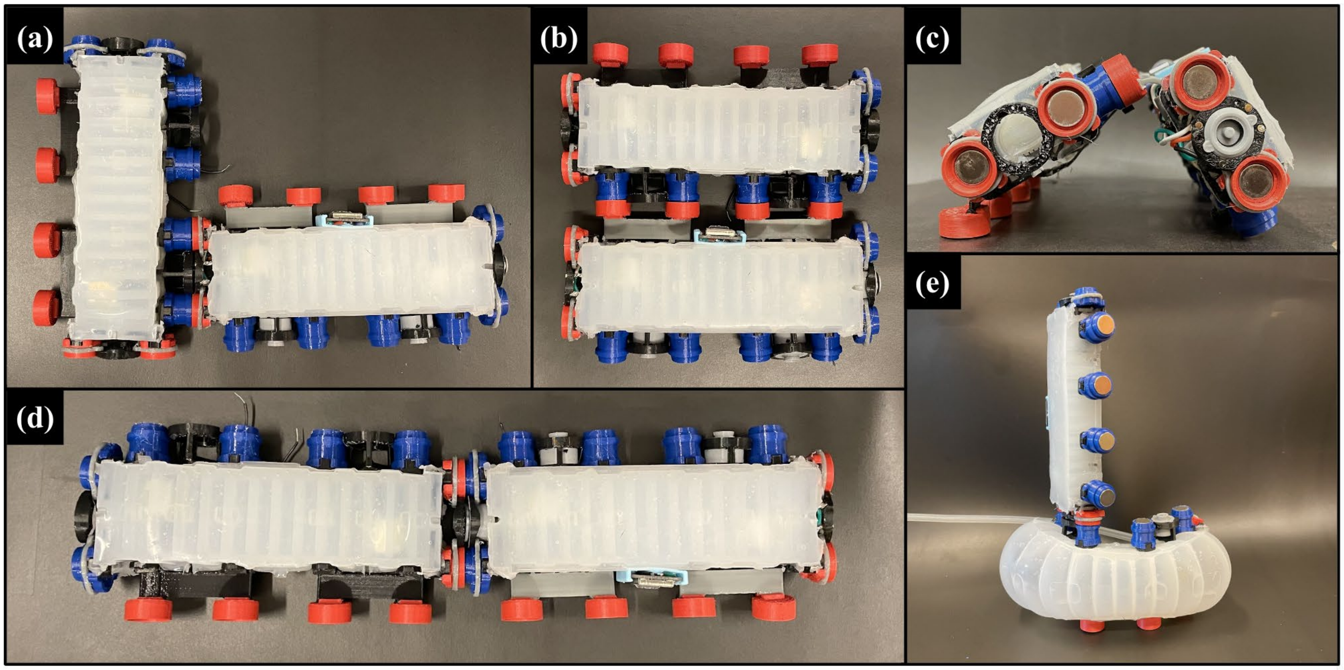

Figure 7. Various reconfiguration combinations of modular actuators assembled manually for demonstration purposes. a) End-to-side type connection. Side-to-side connection in b) planar form and c) spatial form with flexible hinges bent. d) End-to-end connection. e) End-to-side connection in spatial form.

complexity of the system needed to power it (single air and power supply needed), such as the one shown in Fig. 3c. The onboard microcontroller also allows for improved structural optimization and future intelligence.

With the use of centralized PAC connectors and microcontrollers, these actuators are capable of individual intelligence. Each unit could be equipped with a sensor with no additional external wiring. These sensors could include strain gauges to detect the bending angle, accelerometers, and gyroscopes to provide spatial awareness, or simple sensors to detect the location of other units located in the system. Centralized communication allows all the relevant information to be fed back to a single control source. Additionally, external sensor modules equipped with a PAC connector could be attached to the ends of the MPAs via the magnets to provide external information such as applied force, adding additional intelligence to the modules.

The future direction for actuators involves a shift towards streamlining the design through the integration of new 3D manufacturing techniques. The aim would be to eliminate unnecessary rigid components, resulting in actuators that are easier to manufacture and have increased safety when compared to traditional, non-soft actuators. The evolution of 3D manufacturing has yielded the ability to 3D print silicone actuators in a single seamless process [16]. Certain advanced techniques have even enabled the fabrication of silicone components incorporating multiple materials [17]. This not only facilitates the creation of more complex shapes but also enables the incorporation of integrated features such as hinges and connectors. Consequently, this innovative manufacturing approach could yield actuators of higher quality and efficiency, allowing for adoption on a larger scale.

Though not demonstrated, these actuators possess the potential to operate independently from an air and power source through a control module distributing power to all units via the PAC connector. This requires the development of a control module housing a compact air pump and rechargeable batteries, designed to match the physical dimensions of an MPA, thus facilitating seamless integration into diverse unit configurations. The realm of soft robotic actuators capable of untethered operation remains limited, although a few have employed methods similar to those proposed here, leveraging onboard microcontrollers and external battery supplies for actuation [18].

Using a combination of the actuators' abilities to be untethered and the improved intelligence of these actuators, a fully autonomous and easily controlled robotic system could be created utilizing these actuators. Existing systems such as SnapBot [19] utilize modular robotics and a configuration algorithm to produce various methods of locomotion which are dependent on its modular configuration. Based on this same principle, these MPAs could autonomously adapt their control algorithm depending on the task that it needs to complete and the configuration that it was assembled in. With the use of the RMCs, these units could also have the ability of self-assembly.

The benefits of these MagBot modular robots are not limited to using the individual modules but include the ability to be added over time or integrated with existing systems. With a simple integration of a PAC connector within an existing robotic system, the system can be equipped with a tunable, soft robotic gripper. Soft grasping is ideal when grasping irregular or delicate objects, such as produce in the packing industry. The ability to add soft robot capabilities quickly and inexpensively to the system saves the users time and money. In much the same way a motor is used, these modules can be used as actuators in the design of new robotic systems. The PAC connector can allow designers to seamlessly incorporate MagBot into their design, such as the muscles for a robotic arm or movement of assistive devices for wearable device applications.

In summary, our soft modular pneumatic actuator is a versatile device that opens various reconfiguration freedom to quickly customize and create system for on-demand tasks. The key novelty of this design is the tunable, inter-unit connections that allow for versatile configurations using the flexible hinges and reversible magnets with coils. We presented the overall design, including materials used and fabrication of the actuator. We demonstrate the actuators' ability to bend and their high force-to-pressure ratio. The demonstrated potential to completely reverse the polarity of a magnet with a produced magnetic field allows for the tunability of the connections between modules. Lastly, we proposed a new connector that allows for seamless sharing of air pressure, power, and communication between soft robotic modules.

APPENDIX

TABLE 1. PROPERTIES OF REVERSIBLE MAGNET COILS. SHOWN ARE CALCULATED WIRE LENGTH AND CURRENT DRAW FOR DIFFERENT WIRE GAUGE SIZES AND VOLTAGES.

	Magnet Wire Gauge Size			
	24 Gauge	***26 Gauge***	***28 Gauge***	***30 Gauge***
Resistance (ohm)	0.210	0.450	0.905	1.845
Calculated Length (m)	0.249	0.336	0.425	0.545
Voltage (V)	**Calculated Current**			
	24 Gauge	***26 Gauge***	***28 Gauge***	***30 Gauge***
4	19.05	8.89	4.42	2.17
8	38.10	17.78	8.84	4.34
12	57.14	26.67	13.26	6.50
16	76.19	35.56	17.68	8.67

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