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A Shared Electrical-Pneumatic and Reversible Locking Intermodule Connector for Modular Robots

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***Abstract*— With the increasing popularity of modular robotics, there has been an increasing need for reliable and strong connections between module units. This paper introduces two novel connectors, PAC (Power, Air, Communication) and MagLink (Magnetic Link), designed to advance the interconnectivity of modular robots and actuators. The PAC connector centralizes air, power, and communication in a single housing that simplifies integration and minimizes wiring complexities. Meanwhile, the MagLink connector employs a reversible, low power magnetic locking mechanism, ensuring robust and secure connections between robotic components. Both connectors can be integrated in a single compact unit. We characterized PAC connector in terms of maximum pressure, air flow, and sealing capabilities. MagLink was characterized in terms of connection strength, magnetic field/attractive forces to connect, alignment capture space, and power consumption. MagLink advantages are its low power consumption and 13-fold increase in strength compared to the regular magnetic connection. Together, PAC and MagLink herald a new opportunity in modular robotics, offering high force-to-weight ratio (6.4 N/g), high strength-to-power consumption ratio, reliable electrical connection, and pressure handling capabilities of at least 50 psi (0.34 MPa) packaged in a compact design that can be used across a wide range of robotic configurations. This research presents a step forward toward efficient electro-mechanical-pneumatic connectors for self-reconfigurable modular robots, promising practical solutions for a broad range of modular robotic applications.**

I. Introduction

In the ever-evolving landscape of modular robotics, the search of innovative connectors for modular units is paramount to achieve robots' adaptability and versatility. Many existing inter-module connectors rely on permanent magnets or other passive method based connection mechanisms [1], [2]. These types of connection, though reliable, are passive and do not offer self-reconfigurable connection capabilities. Other reversible connectors require higher power consumption, such as thermal connection methods, in which a material is heated and fused together [3], [4]. Electromechanical methods of inter-unit connection prove to have the most versatile and strongest connection as they rely on the mechanical properties of the material of which they are constructed. These types of connections are easily reversible with the inclusion of hooks powered by motors for quick and reliable locking [5], [6], [7].

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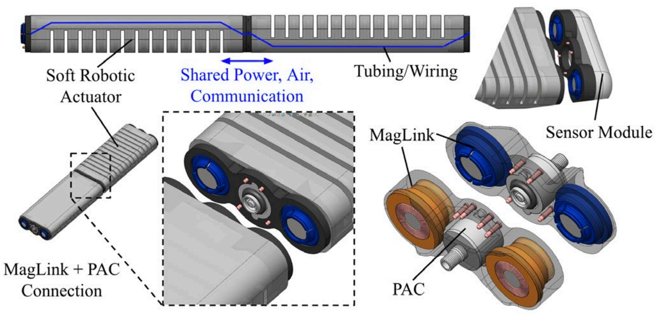

Figure 1. MagLink and PAC connectors being utilized to attach two modular soft robotic actuators together. The PAC connector allows for the seamless sharing of power, air, and communication between modules. Also presented here is the potential for sensor modules to be attached, with power and data being shared through the PAC connection.

However, the inclusion of motors for this type of connection limits the scale at which they can be produced, limiting their implementation in smaller, untethered robotic systems due to increased power demands and larger form factor.

Presented in this paper is a novel solution for inter-unit connections, exhibiting small size, low cost, low power requirements, and reversible mechanical locking. These unique characteristics make the presented connector particularly well-suited for applications where energy efficiency and versatility are paramount, offering a promising avenue for advancement in modular robotics. Fig. 1 shows schematics of such a connector embedded in a soft modular robot as a demonstration example.

In this context, we introduce two types of connectors: the PAC (Power, Air, Communication) connector, designed for seamless integration of power, air, and communication, and the MagLink (Magnetic Link), a reversible, mechanical-magnetic connector designed to securely link modular robots. The MagLink connector utilizes the power of an electromagnet and the physical properties of permanent magnets, to create a robust connection that ensures the physical linkage of robotic modules. What distinguishes MagLink from other magnetic connectors is its innovative and efficient use of an electropermanent magnet, requiring only momentary power to secure a firm, physical connection between modules [8]. Furthermore, this connector transcends conventional magnetic approaches by integrating a novel mechanical locking mechanism, using 3D printed components. The locking mechanism utilizes the physical strength of the plastic components, which lock in place, ensuring a reliable, secure linkage that can withstand the dynamic load demands of modular robots.

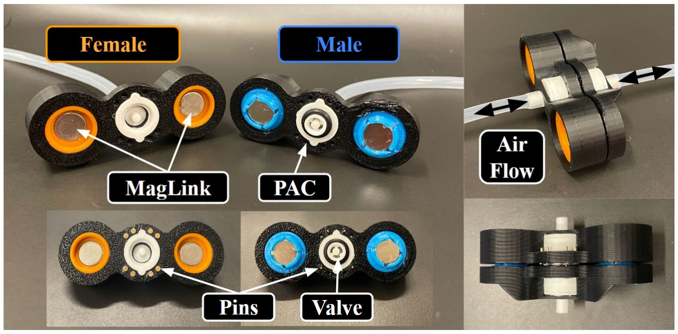

Figure 2. MagLink and PAC connectors integrated into a 3D printed housing. The connectors consist of two sides: male and female. The center PAC valve facilitates air flow between modules and the pins allow for transfer of power and communication. For MagLink connectors, the electromagnets are used to form the initial connection between modules; once connected, the two halves are locked together mechanically using shape locking of 3D printed components.

Complementing the MagLink is the PAC connector, a multifunctional solution that organizes the seamless integration of power, air, and communication channels across interconnected robotic units. The PAC connector addresses the broader need for resource-sharing within a modular robotic connector. The addition of air sharing allows this connector to be used in modular, pneumatically driven soft robotic actuators (Fig. 1). The integrated MagLink-PAC connector offers an all-purpose solution with both physical and resource sharing capabilities for modular robotics, opening new possibilities for applications that demand power-efficient, reliable, and multi-functional connections.

II. Mechanical Design of Connectors

A. MagLink Design

The innovative design of the MagLink connector utilizes dual principles of electromagnetic and mechanical connections with careful material selection and shape design to achieve rigid locking functionality. The connector integrates electromagnetic coils, embedded AlNiCo and neodymium magnets, and a dual-material structure featuring flexible thermoplastic polyurethane (TPU) and structural polylactic acid (PLA) 3D printed components.

The MagLink connector consists of two sides (Fig. 3): a female side that includes an electromagnetic coil and AlNiCo magnet enclosed in a rigid PLA casing, and a male side that consists of neodymium magnets and flexible locking tabs 3D printed from TPU. The electromagnetic coils within the MagLink play a fundamental role in inducing a robust mechanical-magnetic connection. These coils (14 mm OD × 6.4 mm ID × 6.4 mm in thickness) consist of 30-gauge wire wrapped around the AlNiCo magnet (6.4 mm diameter × 6.4 mm in thickness). AlNiCo magnets were specifically selected due to their ability to reverse polarity when exposed to a magnetic field. Fig. 3 shows the schematics of the connection principles. The powering of the electromagnet initiates the movement of a neodymium magnet (10 mm diameter × 4 mm in thickness) on the male side of the connector, and at the same time, alters the polarity of the AlNiCo magnet on the female side. The magnetization of the AlNiCo permanent magnet forms a secure and reversible magnetic bond.

The main advantage of the MagLink connector, when compared to other magnetic connectors, is that it does not rely on continuous electromagnetic forces to stay connected. Instead, the MagLink design utilizes a shape locking mechanism for a mechanical connection with increased strength. The shape locking is achieved through material selections and shape designs from both the male and female sides. On the male side, the TPU material, known for its flexibility, features flexible tabs that respond to the movement of the neodymium magnet. During the locking phase, these TPU tabs can expand radially as the magnet moves. On the female side of the connector, a rigid, grooved PLA structure was designed to act as receptacles for the expanding TPU tabs. When a magnetic field pushes the neodymium magnet, the TPU tabs expand and lock against the PLA grooves. This shape matching design of tabs and grooves ensures that the connection is physically anchored after the initial magnetic contact, enhancing the overall robustness and stability of the MagLink connector.

To disengage the connection, reversible magnetization of the AlNiCo magnet triggers the reverse movement of the neodymium magnet. The elastic TPU tabs radially contract to their undeformed position and the physical TPU/PLA connection unlocks. A comprehensive experimental validation was performed to characterize the connector's performance under different loading scenarios.

B. MagLink Force Calculation

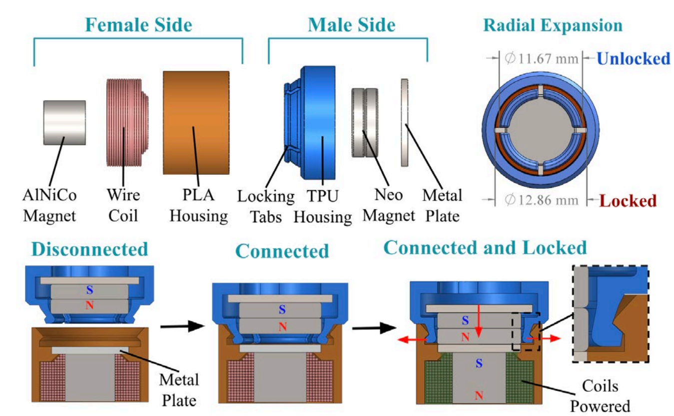

Figure 3. Breakdown of MagLink connector design and locking principle. The connector consists of two sides: female and male. The female side is active, housing the reversible AlNiCo magnet and electromagnet coil. The metal plate inside is secured with glue and provides a flat interface for magnetic connection. The male side is passive, consisting of a flexible TPU housing and permanent neodymium magnets. When powered, the permanent magnets are displaced, locking the flexible tabs into the grove.

The force of attraction between two magnets can be calculated using the Coulomb law for magnetism [9], where the force between two magnetic poles is inversely proportional to the square of the distance between them. Mathematically, this relationship is expressed as:

$$F = ku_0(m_1 m_2)\,/(4\pi r^2) \qquad (1)$$

where F represents the force of attraction, k is the magnetic constant, m_1 and m_2 denote the strengths of each magnet, respectively, and r signifies the distance between them. By applying this equation, the calculated attraction force between the male/female magnets provides insights into the scaling of the MagLink design, which leads to more accurate estimations of the desired strengths and capture workspace for the connectors. These estimations were compared against values obtained from the experimental testing in Section III.

C. PAC Connector Design

The PAC connector utilizes a combination of a 3D-printed air valve and strategically placed pogo (spring-loaded) pins to facilitate the transfer of power and communication (Fig. 4). The key feature is a custom designed, 3D-printed air valve that introduces adaptability and precision to the pneumatic air transfer. Complemented by a spring mechanism and O-rings, this valve remains sealed until engagement, ensuring controlled airflow once connected.

The pogo pins are mirrored on two sides (Fig. 4), allowing for two connection orientations to enhance its adaptability. The maximum operational current for the pogo pins/connector is 5 A. Their spring-loaded design ensures secure contact, allowing for efficient and stable transmission.

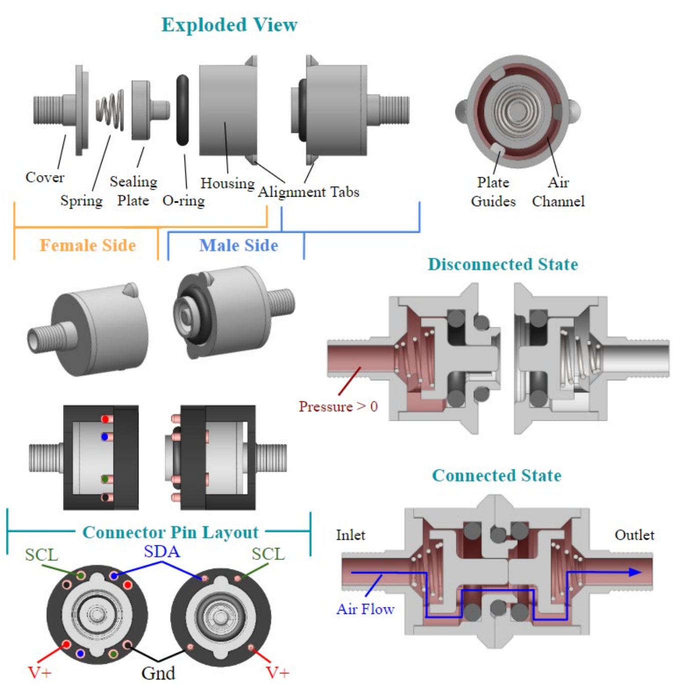

Figure 4. PAC connector valve design. Exploded view shows the internal 3D printed components, spring, and O-ring used for sealing the connection. The pin layout is arranged in a way that allows two orientations of connection. The cross-section views show the valve in disconnected and connected states. The sealing plate is pressed against the O-ring until connection is made and the sealing plates are pushed in.

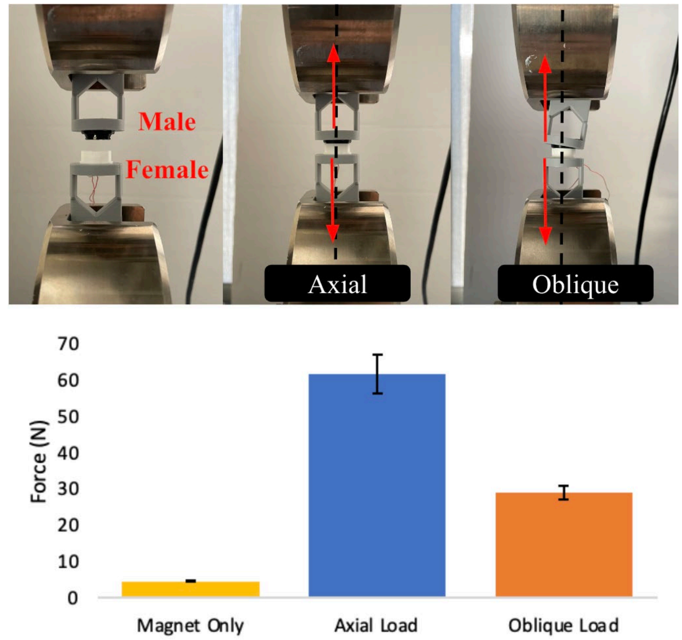

Figure 5. Experimental testing of MagLink's maximum strength under axial and oblique loads (top). The result comparison of magnet strength with and without engagement of the MagLink (mean and standard variation) of nine tests.

The utilization of widely used two-wire communication protocols like I²C and TWI ensures reliable data transmission between modules. In a test with master and slave microcontrollers, the slave controller was able to receive power and commands, with measured latency over the I²C connection at 516 µs, or 258 µs one way. The deliberate choice of a physical connection over wireless communication allows a sturdy link between modules and facilitates unit-to-unit identification, which is crucial for enabling self-reconfiguration and control.

III. Experimental Validation

A. MagLink Strength

The MagLink connector has distinctive advantages of high connection reversibility and exceptional connection strength, suitable for modular robots on the centimeter scale or larger. To showcase its robustness, the connector's strength and alignment requirements were tested using a tensile testing machine. Fig. 5 shows the experimental setup used to test the maximum connector strength with both axial and oblique loads. When the connector relies solely on magnetic attraction forces between the embedded magnets, the axial separation force is only 4.5 (±0.1) N. However, when the MagLink connector was securely locked together using the 3D printed TPU/PLA locking components, the connector withstood 61.7 (±5.2) N of pulling forces before separation occurred. This 13-fold increase in strength highlights the superior performance of the MagLink connector, showcasing its capacity to withstand forces far beyond what traditional magnetic connections can handle, while still being reversible and allowing easy disconnection.

The failure of the connector due to axial loads was the result of the extension of the TPU tabs, but no permanent deformation or breaking occurred. These loads could further be improved with optimization to the tab and groove design, relying more on the mechanical properties of the material. Larger tolerances were used in this design to allow for more alignment error and ease of connection between modules.

Furthermore, the connector's resilience was tested for non-axial loads, simulating the operational forces and torques experienced by modular robots when connected to adjacent units. The MagLink connector withstood simultaneously applied 360 N·mm of estimated bending torque and 28 (±1.8) N of axial pulling force, which was more than 6 times the regular magnetic force. This force was applied by rotating the testing rig housing of the male end of the connector, as shown in Fig. 5. This caused a point load on one side of the connector, inducing torque. The increased strength observed in these experiments emphasizes the connector's adaptability to real-world scenarios and its reliability in maintaining structural integrity despite the presence of combined loads.

B. Electromagnet Power Consumption

Ideal connectors for modular robots must exhibit not only high connection strength, but also high-power efficiency and low energy consumption. The MagLink reversible connector exhibited a high strength-to-power consumption ratio. The connector demands only a momentary burst of 24 A at 12 V, lasting approximately 50 msec. This transient, brief burst is powerful enough to induce the required polarity reversal in the AlNiCo magnet. The burst of energy (E_{burst}) required for this process applies 288 W of power (P) for a duration of 50 msec (Δt). Expressing $E_{burst} = P \times \Delta t/3600$ in watt-hours (Wh) results in a total consumed energy of 0.004 Wh. The calculated nominal energy consumption (E_{cons} (Ah) = E_{burst}/V_{burst}) is approximately 0.33 milli-A-hours during this momentary burst when engaging or disengaging the connectors.

Once the connection is established, the structure stays connected based on the mechanical locking mechanism without consuming any further electrical energy. The overall power consumption is low, making the MagLink connector a standout choice in terms of energy efficiency. Combining the high force-to-weight ratio (6.4 N/g), high strength-to-power consumption ratio, and improved energy efficiency, the MagLink connector not only ensures an optimal use of power resources but offers a sustainable and reliable connector solution in modular robotic applications.

C. Attraction Forces Between Male and Female MagLink Side

Fig. 6 illustrates the magnetic attraction force as well as the permissible radial and angle variations between the male and female sides of the connector for initiating a successful connection. These results showcase the magnetic attraction capabilities of the MagLink connector before locking. The concave/convex nature of the connector allows for a wide operational range for the two sides to make connections, even when they are misaligned, with a maximum angle of 22°. The connector's angle and capture envelope outline the allowable range within which the connector can connect without the possibility of becoming jammed. It is important to note that the connector must be fully in place before the MagLink connection can be securely locked. The theoretical and experimental results of the relationship between the attraction force and the distance between the magnets are highly correlated with both curves following the principles of the inverse square law. These results provide insights into the connector's ability to initiate a connection prior to locking.

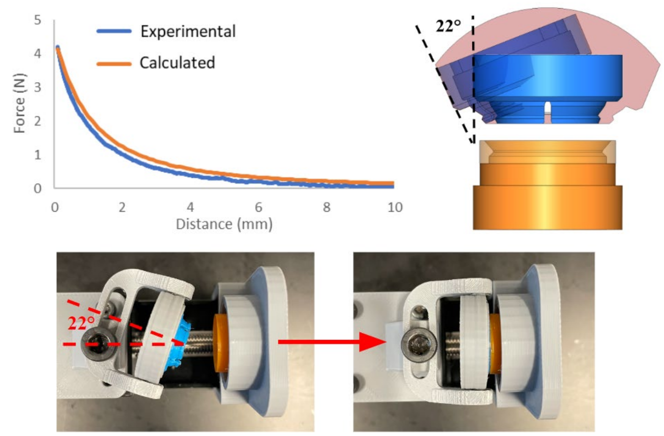

Figure 6. Relationship between distance and attraction force for embedded magnets in the male and female side of the MagLink connector. Results show the experimentally measured force and force calculated from the measured magnet strength and Coulomb law equation. The CAD view shows the permissible approach angle range when the connector can still initiate connection. The bottom figures show how the permissible angle was experimentally obtained with the use of a linear actuator holding the male side.

D. Attraction Air Through PAC Connector

The PAC connector was experimentally tested to validate its pressure handling and air flow capabilities. Air flow rates were recorded at various pressures (0-12 psi) for an unobstructed silicone tubing and for flow through the PAC connector (Fig. 7). This pressure range was the maximum that could be reached through the unobstructed, 1/8” diameter tubing in this setup. Results showed a small decrease in air flow when the connector was added to the system, requiring an increased pressure of ~1.5 psi to obtain the same air flow rate. In addition, while the connector decreases air flow slightly, the change in flow rate is observed to be lower when the connector is operated at lower pressures.

Failure and leakage tests were conducted to analyze the connector's reliability and resilience. The connector was tested

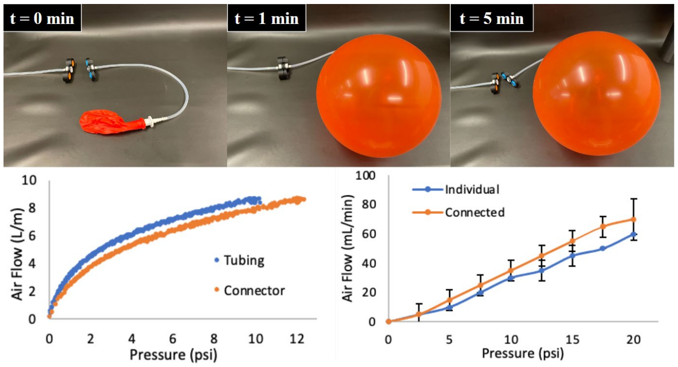

Figure 7. PAC air connector testing. Visual demonstration with a balloon of the PAC connector's ability to transfer air and seal once disconnected. Data representing the air flow rate through the connector and through an unobstructed silicone tubing at various inlet pressures. The individual and connected data represents the air flow through the sealed connector at varying pressures due to leakage.

at varying pressures, ranging from 0-20 psi, by measuring the flow rate to detect signs of leakage. The first test consisted of just the individual connectors, namely the male and female sides, relying solely on the sealing capabilities of the valve in its unconnected state. The results from these individual connectors yielded identical outcomes, as both sides incorporate the same sealing mechanism. Additionally, the test was repeated with the two sides engaged, relying on the MagLink connectors to keep the valve in place.

Comparison of the two tests showed that the system experienced a small leakage due to the connectors (Fig. 7 bottom right). The relationship appears to be linear, measuring a flow rate increase of ~3.5 mL/min for every 1 psi increase in pressure. The individual connectors showed slightly less leakage than that of the connected state. At the maximum pressure tested of 20 psi, the system leaked ~70 mL/min. This leakage is mainly the result of the seal between the O-ring and the 3D printed valve, an issue that could be resolved with the use of softer O-rings or alternative sealing interface. Despite the small leakage, the PAC connector design proved its suitability for short-term, low-pressure applications in modular robotics.

Fig. 7 highlights the PAC connector's capability to transfer air seamlessly while ensuring a secure seal upon disconnection. The PAC connector was designed to facilitate the transfer of air from either side of the connector, whether it be the male or female end. Upon disconnection, both ends of the connector automatically seal, maintaining air pressure and preventing leakage. As illustrated in Fig. 7, the balloon attached to the male end of the PAC connector exemplifies this functionality. Upon connection with the mated side, the balloon receives a steady flow of air. Even after disconnection, the balloon retains its air pressure, highlighting the effectiveness of the PAC connector in pneumatic applications.

To test the connector's maximum pressure handling limits, the connector was subjected to air pressures reaching up to 90 psi through a ⅛ inch ID silicone tube. Up until 50 psi, no significant air leakage was detected when in a connected state or on any individual side when not connected. Once the connector was subjected to pressures higher than 50 psi (up to 90 psi), leakage occurred due to expansion of the silicone tubing. These results highlight the connector's ability to maintain a secure seal even under substantial stress and resulting failure of the connected tubes prior to the connector. The connector disconnected at a pressure averaging 90 psi due to separation of the MagLink connector. However, it is worth noting that most pneumatic driven soft robots reported in literature operate under 20 psi; therefore, the high-pressure limit of 90 psi demonstrates the MagLink connector's ability to withstand forces far beyond its intended applications. In addition, through optimization or scaling of the design, the operation limit can potentially be further improved.

IV. Discussion

As demonstrated through the design and experimental validation of these connectors, PAC and MagLink emerge as promising solutions to facilitate the interconnectivity of modular robots and actuators. Engineered with meticulous attention to force, power, and air requirements, these connectors were tailored specifically for integration with modular robotic actuators, including soft actuators (Fig. 1).

The principles exemplified in their design and functionality hold promise for scalability. By scaling these connectors to larger sizes, the potential for greater air flow, increased pressure, and enhanced inter-unit connection strength becomes apparent. This scalability opens the number of possibilities for diverse applications, enabling seamless integration into a wide range of robotic configurations.

The PAC connector was engineered to pave the way for future untethered connections among pneumatically driven, soft robotic actuators. By establishing a centralized hub for air, power, and communication, it effectively streamlines the design and operation of modular robotic systems. This centralized approach minimizes the need for extensive tubing and wiring of individual actuator connections, resulting in a simpler modular design. Additionally, the centralized connector facilitates the addition of extra units to the robotic configuration without necessitating alterations to coding, additional wiring, or adjustments to the air supply. Along with additional units, the use of centralized power and communication wiring allows for sensor modules, such as force sensors, cameras, etc., to be attached to these robotic units seamlessly.

On the other hand, the MagLink connector through its reversible inter-unit capabilities empowers seamless disconnection and reconnection, offers versatility and adaptability in robotic configurations. Furthermore, the low energy demands render them conducive to untethered robotic control through onboard batteries, enabling greater flexibility and mobility in robotic operations.

The PAC connector tackles the issue of air transfer between modular robots and makes it seamless and easy to attach additional modules. There exist very few pneumatic connectors that allow for passive disconnection. Current methods use an open, centralized channel for transferring air and other gasses [10]. Since there are no valves in these systems that seal like the PAC connector, disconnection and reassembly of robotic systems that utilize these connections proves difficult. When it comes to locking units together, the MagLink is a unique choice compared to the existing connectors due to its incredibly compact size and high strength-to-weight and size ratios. With integration of two MagLink and one PAC connection, the presented connector assembly is only 55 mm × 20 mm × 10 mm in size and weighs only 60 grams (both sides), which is significantly smaller than most electromechanical connectors, as most of these connections require the use of motors [5], [6], [11]. This smaller size allows for robots to be scaled down and allow for the integration of more connections for increased arrangement possibilities and applications.

While we recognize certain limitations with this connection, notably its high current requirement for activation, potential solutions exist to overcome these issues. One approach to mitigate this issue is to sue smaller gauge wire in constructing the electromagnet coil, at the cost of additional voltage requirements. Additionally, we acknowledge that the use of these 3D printed valves in the connectors can result in a reduction of air flow through the system. This air flow reduction can be mitigated through additional optimization and improved manufacturing of the 3D printed valve. The advantages offered by these connectors in modular robotics, such as seamless integration of air, power, and communication, alongside a compact, low-power electromechanical connection, significantly outweigh these drawbacks.

Future iterations of the PAC connector may leverage the use of advanced manufacturing technologies, such as stereolithography 3D printing, to further enhance their functionality and versatility. This advanced printing method offers finer resolution and tighter tolerances, enabling the production of connectors with increased flow rates and reduced dimensions. In addition, future iterations of the PAC connector are set to integrate custom PCB boards as the receiving pins. This innovative approach promises simplified wiring between connectors, eliminating the need for complex wiring configurations and minimizing the risk of errors during assembly. Moreover, the adoption of custom PCB boards opens possibilities for expanding the connector's capabilities [2]. By accommodating additional pins, future PAC connectors can support a broader range of positions, transitioning from two possible positions to four or even infinitely variable positions with the adjustments of pin locations. These improvements could further enhance the connector's flexibility and adaptability, catering to a wider array of robotic configurations, control methods, and applications.

V. Conclusion

In summary, this paper presents the design and evaluation of two novel connectors, PAC and MagLink, for modular robots. The PAC serves as a flexible and efficient means of pneumatic and power sharing within modular units. The MagLink connectors, on the other hand, provide high strength and reliable, electrophysical interconnections between modular units, facilitating seamless reconfiguration and assembly. Both connectors were experimentally tested through rigorous experiments to validate their functionality. The results show significant promise in terms of performance, reliability, and adaptability. Their innovative features and scalable design pave the way for enhanced interconnectivity, simplified operations, and expanded possibilities in the realm of robotic applications.

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