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Extended Abstract for ASPEN2022 Development of a Pneumatic Module for Reconfigurable Soft Robots

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Reconfigurable soft robotic system is an emerging research field with the potential to make significant technological advances to future robotics. Reconfigurable soft robots can deliberately change their own shape with variable morphology, in order to adapt to confined environments, perform wide range of tasks, avoid causing damage, or prevent injury to co-workers. They possess many advantages such as high versatility, high value, and high robustness which may lead to a radical change in automation. In this work, a pneumatic soft actuator module is developed to expand the flexibility and dexterousness of soft robots. The hexagonal structures can provide minimal density, rapid response, high compression properties, high elongation rate and crush resistance, compared to hollow soft chambers. A blocking force of 45 N is achieved by a single soft chamber. This payload capability is beyond the maximum requirement for use at small scales where most soft robot applications are applied. The modular design adapts the concept of 'plug and play', which integrates all electronic and pneumatic components in the module through a common power and vacuum supply, allowing soft robots with many actuator modules to maintain simplicity and ease of implementation, especially by achieving scalability and avoiding problems with excessive cabling and routing when the degree of freedom increases. The developed pneumatic modules can be assembled in series to achieve a desired working envelope, and a high degree of kinematic maneuverability and flexibility can be achieved for manufacturing, machine maintenance, inspection, security checks, rescue, and space exploration tasks. It can also be used individually as an end-effector or a parallel platform to perform tasks in healthcare, biomimicry, and human-robot collaboration.

1. Introduction

Modular reconfigurable robots consist of repeated modules that can be interchanged or reassembled to deliberately change the shape of the robot by rearranging the connectivity of the modules. The reconfigurable robotic system can change its shape to suit specific tasks, adapt to changing environments, avoid causing damage, or prevent injury to co-workers. They possess many promises such as high versatility, high value, high robustness, and low cost.[1]

Although the concept of reconfigurable robots emerged in the 1970s when an end effector with automatic tool changers was introduced in computer numerical controlled machining centres,[2] most of the developments are based on conventional robots.[3-6] In recent years, soft robotics, a subfield of robotics that makes use of compliant materials, is emerging fast. Differs from rigid-bodied robots built from metals, ceramics, and hard plastics with rigid links, soft robots are made of rubber, plastic, or silicone and make use of hydraulic fluids or air to carry out their functions. The inherent compliance of soft robots can improve their safety when working closely with humans. They are used in many application fields such as rehabilitation[7], animal studies[8], disaster relief[9], replication of human muscles[10] as well as internal deployment inside the human body[11].

However, in many situations, such as exploration, search, and rescue, the tasks to be performed or the surrounding environment is usually unknown, which presents significant challenges in manufacturing suitable soft robots in advance and in completing tasks quickly. In such situations, the reconfigurability of soft robots becomes significant. Reconfigurable soft robots can be further adjusted to different working environments and reduce the preparation time for specific tasks.[12-13] In this work, obtaining inspiration from hexagonal structures, we developed a pneumatic soft actuator module to realize the "building bricks" of reconfigurable soft robots. With three vacuum-driven soft chambers and onboard electronic components, the actuator module design adapts the concept of 'plug and play' and maintains simplicity and ease of implementation, especially by achieving scalability and avoiding problems with excessive cabling and routing when the degree of freedom increases.

2. Results

2.1 Mechanical design of the pneumatic soft actuator module

The vacuum-driven soft chamber consists of a silicone outer sheath which creates an enclosed airtight envelope, and a hexagonal structure acts as an inner scaffold to support the airtight envelope and create deterministic shapes, quicker response, and greater load bearing capacity. Compared to hollow pneumatic chambers, this structure requires smaller strains to achieve large deformation so that we can use stiffer materials to fabricate the chamber, and it can return to its original shape fast after removing the vacuum supply. Additionally, with different pneumatic stimuli, external forces or constraints, a single chamber can achieve stretching, contracting, and bending while maintaining stable shapes. A blocking force of 45 N is achieved by a single soft chamber when subjected to a vacuum level of 90%. This payload capability is sufficient for use at small scales where most soft robot applications are applied.

The three soft chambers are evenly spaced in a triangular configuration (Fig. 1) to provide 2 degrees of freedom motion in a 3-dimensional space. The chambers are fixed to the top and bottom plates by screwing the rigid connectors with the plates. This will avoid the delamination between soft and rigid components, which is commonly observed in soft and hybrid robots.

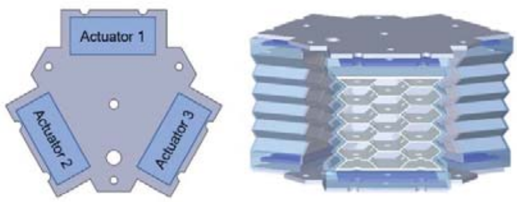

Fig. 1 Configuration of the three soft chambers (left) and the design schematic of the pneumatic soft actuator module (right).

2.2 Development of the on-board control system

To achieve the concept of “plug-and-play”, all electronic components, including pressure sensors (MPXV6115V, NPX), solenoid valves (LHDA0531115H, The Lee Company), and the wireless microcontroller module (ESP32, Espressif Systems) are integrated on a printed circuit board (PCB). Each soft chamber is connected to two solenoid valves, one to the vacuum supply and the other to the atmosphere so that the pressure inside the chamber is controlled by the two solenoid valves. A vacuum pressure sensor is also connected to each soft chamber, forming a closed loop to provide feedback to actively control the pressure. The detailed architecture of the integrated soft actuator module is shown in Fig. 2.

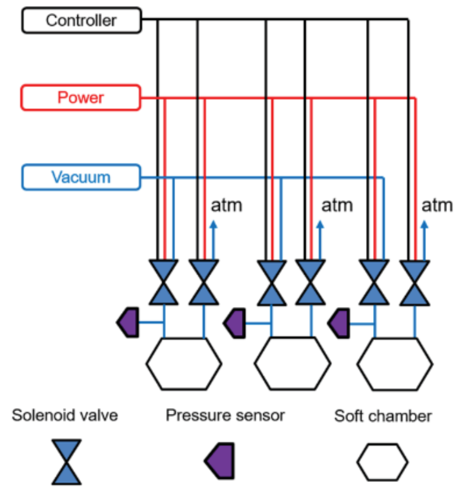

Fig. 2 Integrated architecture of the soft actuator module. Each soft chamber is connected to two solenoid valves, a pressure sensor and a dedicated channel of a microcontroller.

The entire soft actuator module weights 400 g, and the bill of materials to fabricate the actuator is summarized in Table 1.

Table 1 List of components in the soft actuator module

Component	**Quantity**
Soft chamber	3
Solenoid valve	6
Microcontroller	1
Vacuum pressure sensor	3
Flat plate	2
Screw	6
2mm ID silicone tubing	9
5mm ID silicone tubing	1

When subjected to vacuum, the activated soft chamber collapses to provide tensile force and linear strain, resulting in an angular deflection between the top and bottom plate. With three vacuum-driven soft chambers, the soft actuator module can provide two-degree-of-freedom bending motion in three primary directions. We actuated each soft chamber 10 times to verify the effectiveness and repeatability of the soft actuator module. The experimental results in Fig. 3 present the bending displacement as a function of time during actuation. It can be observed that all three primary directions can achieve a 24mm displacement with respect to the reference state at the tip edge of the actuator. During the actuation cycles, the discrepancies between each cycle when actuating the same chamber are small. Additionally, inconsistencies in displacement when actuating three different chambers are almost negligible.

This experimental verification confirms that the hexagonal inner skeletons create more deterministic shapes, and the fabrication techniques are reliable to create identical soft actuator modules with consistent performance. Compared to positive pressure actuator modules,[14] soft vacuum actuator modules have several advantages. First, the soft chambers will only shrink, thus there is no extra space required upon activation. Second, soft vacuum actuator modules offer a unique fail-safe feature since they can prevent overactuating beyond the material limitation, while positive pressure soft actuators result in high-stress gradients. Finally, soft vacuum actuator modules are more reliable and durable as they exhibit less vibration and more accurate movement.

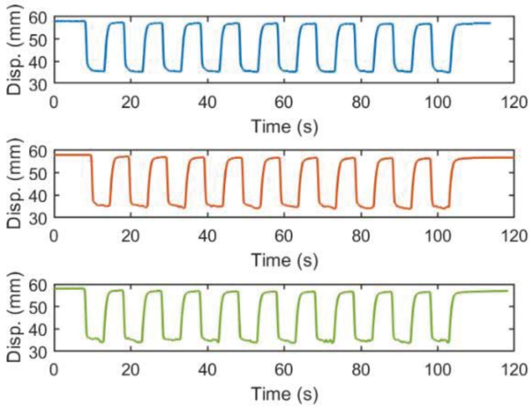

Fig. 3 Experimental results of actuating each soft chamber with the same vacuum pressure stimuli.

3. Conclusions

In this work, we developed a pneumatic soft actuator module which can provide two-degree-of-freedom bending motion with three vacuum-driven soft chambers inspired by hexagonal structures. The hexagonal structures possess advantages such as minimal density, rapid response, high compression properties, high elongation rate and crush resistance. A maximum blocking force of 45 N is achieved by a single soft chamber. With the concept of ‘plug and play’, the developed pneumatic soft actuator modules can be assembled in series to achieve a soft manipulator with a high degree of kinematic maneuverability and flexibility that can be achieved for manufacturing, machine maintenance, inspection, security checks, rescue and space exploration tasks. Since the soft actuator module integrates all electronic and pneumatic components on itself through a common power and vacuum supply, fast assembly of soft robots with many identical modules can be achieved while maintaining simplicity without excessive cabling and routing when the degree of freedom increases. The soft actuator module can also be used individually as an end-effector or a parallel platform to perform tasks in healthcare, biomimicry, and human-robot collaboration. This concept is more robust and adaptive than conventional systems, yielding more efficient soft robots with higher-order pneumatic systems and many degrees of freedom, which can lower overall robot costs by making complex machines out of mass-produced modules. It has the potential to evolve into a new approach to robotics and a highly interdisciplinary research field in the next few decades.

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