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A Compact Low-Cost Electronic Hardware Design for Actuating Soft Robots

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***Abstract*—A low cost, compact embedded design approach for actuating soft robots is presented. The complete design and mode of operation was demonstrated, and the production of the complete system was also demonstrated by building a microcontroller based hardware system which was used to actuate a soft robot for bending motion. The whole system including the electronic circuit board and actuation components was embedded in a 3D-printed casing to ensure a compact approach for actuating soft robots. Results show the viability of the system in actuating and controlling silicon-based soft robots to achieve bending motions. Qualitative measurements of the bending distance and pressure were obtained using this system. This electronic design is easy to reproduce and integrate into any specified soft robotic device requiring pneumatic actuation.**

Keywords–soft robots; electronic circuit; PCB; microcontroller;

I. Introduction

Soft robotics is currently an active area of research [1]–[5] as soft actuators are relatively inexpensive to manufacture. The compliant structure of soft robots allows novel motion and grasping tasks that are difficult to implement with rigid parts [6]. Their compliant nature allows them to be placed in direct contact with the surface of the skin [7] to provide the necessary assistive force through pressure control. These robots are considered soft due to their intrinsic property: the materials from which they are made are compliant and resilient. Soft robots are actuated by only compressed air, they are capable of producing many degrees of freedom for a single actuation source and so are under-actuated. Therefore, pressure control becomes very important when actuating these robots. In order to provide a compact embedded system for pressure control of soft robots, a low cost pressure regulator for robotic application was designed. In this work, an integrated electronic control system and pulse width modulated solenoid valve control the output pressure proportionally to an internal feedback through an integrated pressure sensor.

The effectiveness of pneumatic pressure controllers has been confirmed through step response experiments, both for PWM-controlled on/off valves [8] as well as for different types of servo valves [9], [10]. Previous work on methods of actuating soft actuators is majorly with the use on/off solenoid valves to control the flow of pressurized air to the actuators [1], [2]. Nonetheless, a complete electronic hardware system for the actuation of soft robots has not been demonstrated so far.

This paper reports the design of a MCU controlled and operated pressure regulator system to perform actuation of soft robots. In order to achieve this low cost system, inexpensive electronic components and 3D printing technology was used. This system offers flexibility since it can be integrated with computer vision system and modified to receive a digital control or analogue signal as input. A computer program written in C language was implemented for valve control in order to produce an output signal that corresponds with a desired output pressure.

The main contribution of this paper is to present a compact, low cost, easy to manufacture hardware system and associated control circuitry for the actuation of pneumatic soft robots. The pressure regulator system consists of a 6VDC air pump, solenoid valves, the MCU control system built on a PCB and a 3D printed case which embeds the whole system to make it low cost, compact and easy to redesign and implement. The ease of production and low cost provides a suitable alternative to expensive off-the-shell electro-pneumatic regulators in the market.

II. System Overview

The main aim of this system is to regulate the pressure of compressed air from a pressure source using a low cost and compact electronic circuit such that the output pressure is directed to actuate soft robots. The use of an electropneumatic regulator for this purpose would be expensive. Furthermore, the use of mechanical systems such as cylinders, piston pump would be cumbersome and make the system bulky. Therefore, it is necessary to design a compact electronic system for use in soft robotics.

The system is composed by two main parts, the embedded control on a Printed Circuit board, and the design of a compact structure to house the complete pneumatic system so that portability is ensured. Figure 1 shows the block diagram of the proposed application. The input signal is used to set the desired pressure. The realization is by an

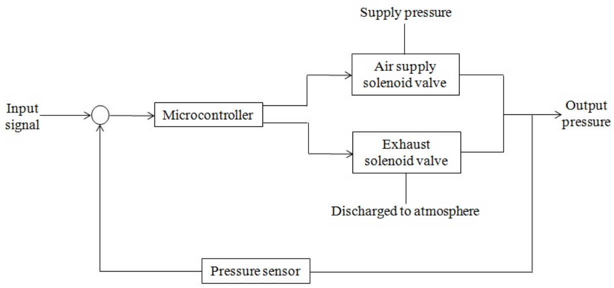

Figure 1. Block diagram of soft actuator pressure controller

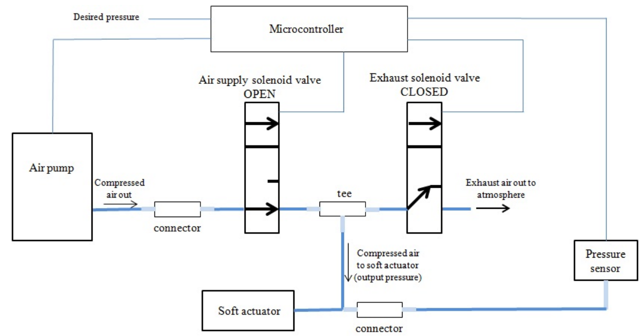

Figure 2. Circuit arrangement of soft robot pressure controller

8-bit microcontroller (MCU), a PIC16F876A of Microchip running at a clock speed of 4MHz. The MCU system is able to actuate a soft module by reading pressure values via the analogue inputs of the microcontroller. The solenoid valves are controlled by 2 output compare modules configured for PWM-mode. As no operating system kernel is used, mainly interrupt sub-routines and parallel running subunits are used. This works very well for analogue input of pressure signals.

For control of soft actuators by an MCU, 1-way/2-position normally closed solenoid valves was used, (2 valves are required for one actuator) one for inflation (inlet solenoid valve) and the other for deflation (exhaust solenoid valve). Solenoid valves control the flow of air into and out of the actuators. Furthermore, 6V solenoid valve having a power rating of 2.25W solenoid valve, a maximum operating pressure of 350mmHg; exhaust speed of 4s and leakage of 3mmHg/minute was used. These solenoid valves are light and compact enough to be integrated as demonstrated. For higher pressure system, higher pressure valves are needed. This can be achieved by either operating two or more solenoid valves in parallel as one logical valve or simply using valves with higher pressure.

Pressure control is used to control the motion of a soft actuator. To measure pressure, amplified pressure sensors (0 - 5psi pressure range) with analogue interface was used having a 1ms response time and a 10 bit ADC resolution was used to read the pressure. Using the MCUs PWM features, pressure is controlled by varying the length of the duty cycle. In this case a duty cycle has a maximum length of 1ms. The output pressure is also dependent on the type of valve, power supply voltage, and pressure difference. This means a specification for the inlet and exhaust solenoid valve (inflation and deflation) is needed. For the inlet solenoid valve, the pressure difference is given by the constant supply pressure and the actual pressure in the actuator. For the exhaust solenoid valve, the pressure difference is between internal pressure and the atmospheric pressure.

III. Design Implementation

A. Pressure Regulator Circuit

Figure 2 shows the arrangement of pumps and valves for the actuation of soft robots in order to carry out inflation and deflation cycles. As shown, it consists of an air pump to act as the pressure source; two solenoid valves (one acts as an air supply valve while the other as an exhaust valve) and a pressure sensor to measure the air pressure in the soft actuator.

Compressed air from the pump passes through the air supply solenoid valve and changes to output pressure when the air supply solenoid valve turns ON. Therefore, air from the supply pump passes through the air supply solenoid valve and changes to output pressure. A PWM output is then produced on the output pin of the MCU to switch ON/OFF the exhaust valve in order to produce an output pressure equal to the desired pressure. The exhaust valve is also used to deflate the soft actuator this is essential for crawling [2] or snake like [3] motion of soft robots. The output pressure is fed back to the MCU via the pressure sensor. This is to check if the desired pressure has become equal to the output pressure. Pressure corrections then occur to produce an output pressure that is equal to the set pressure. Once the pressure sensor has sensed that the desired pressure is equal to the output pressure, the exhaust valve will turn OFF (closed) in order maintain to a constant pressure.

More than one separate individual units of a soft actuator can be controlled using this system. This would be achieved by the addition of two valves for every separate air channel. This is a low pressure controller system that operates at about 0 to 5psi; since the pressure range of the pump and solenoid valves are between 0 - 6 psi. Soft actuators operate within this pressure range and so this system is suitable for actuating soft robots. To achieve a high pressure system, this pressure regulator circuit is easy to scale up by using a high pressure pump and solenoid valves.

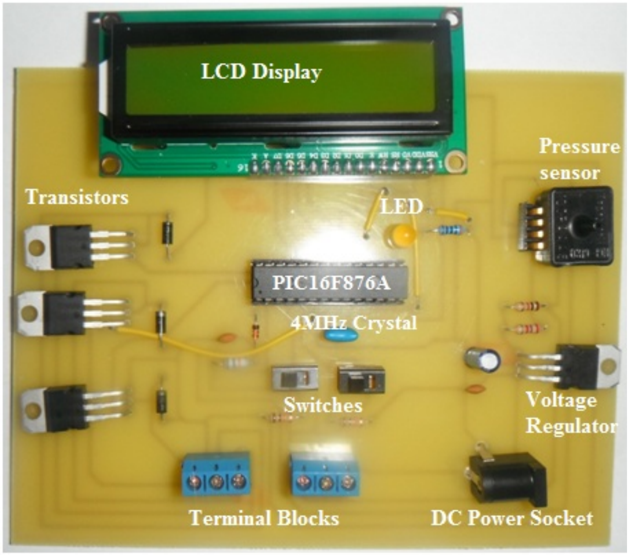

Figure 3. Produced Printed Circuit Board

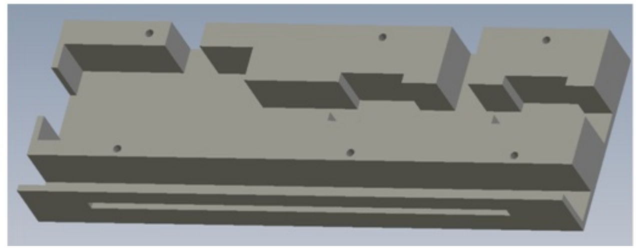

Figure 4. 3D casing for valves and pump in SolidWorks

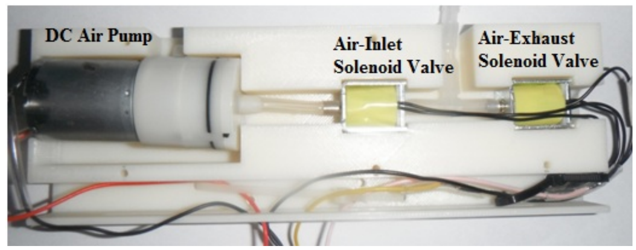

Figure 5. 3D Printed casing housing the valves and pump

B. Production of PCB

The pressure regulator circuit was implemented on a printed circuit board as shown in Figure 3 to achieve a compact and portable system. The components used include the following:

1) Microcontroller: The PIC16F876A microcontroller is the brain of the regulator system. Here, control commands are written to inflate/deflate the robot, read the system pressure from the pressure sensor to be used as an appropriate feedback and write the current pressure on the LCD display.

2) Yellow LED: The LED was used as an indicator for the system.

3) LCD: This was used to display the output pressure. It acts as an indicator for the user of this embedded system.

4) ON/OFF Switches: When Switch 1 is turned on the indicating LED would come ON. Switch 2 is used to turn on/off the valves and pump so that the user has control of the start and stop operation of the system.

5) Pressure Sensor: The pressure sensor monitors the pressure of the regulator system.

6) Transistors: It was used to interface the high current external devices to the microcontroller. The pump and solenoid valves make use of high current and cannot be directly connected to the digital I/O pins of the microcontroller. Transistors were used for the solenoid valves and pump to drive them at their appropriate current while ensuring that they are controlled by the MCU. When the output pin of the MCU to which the valve/pump is connected to is high (5V), the transistor is active, when the output pin is low (0V), the transistor is off. In general, the transistor is used to switch current on and off to the solenoid valves and pump; through the transistor, a small current supplied by the microcontroller will switch on a large current that drives the valves and pump.

7) Diodes: These were used as flyback diodes for the valves and pump. When the pump or valve is subjected to a large change in current, like when the transistor switches, the inductor in the pump and valves presents a large back-emf (back-electromotive force or voltage). This large voltage spike could be harmful, so flyback diodes were required to dissipate this spike.

8) Power Supply: This regulator system was powered by a 6V DC power adapter plugged to a socket outlet.

9) Voltage Regulator: The voltage regulator was required to produce a 5V DC output from the 6V DC input in order to power up the PIC microcontroller at the appropriate voltage.

10) Terminal Blocks: They were used to connect the wires from the valves and pump to the circuit board layout as shown in Figure 5.

C. Production of 3D-Printed Casing

A 3D casing for the valves and pump was designed using SolidWorks 3D CAD design software (Figure 4). This was done to act as housing for the pump and solenoid valves so as to achieve a fully embedded and compact system. The 3D model was printed with ABS plastic using a 3D printer. Figure 5 shows the solenoid valves and pump inside the 3D-printed casing.

The completed hardware system including a one-channel soft robot is shown in Figure 6. A silicone tubing is connected from the pressure sensor to the inlet of the silicone soft actuator as shown to measure the air pressure therein.

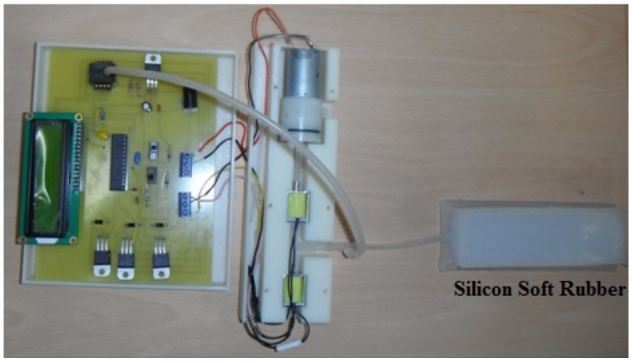

Figure 6. The complete setup for soft actuation

IV. Performance Evaluation

The PIC16F876A switches its output pins between 5V and 0V to create a PWM signal for controlling the speed of the air pump. PWM works because the motor in the air pump has rotational inertia that filters out the fast switching. Therefore, the rotational inertia of the DC motor inside the pump smoothens out these rapid pulses provided by PWM and the result is a slower axle rotation and consequently regulating air pressure. For the case of the solenoid valves, PWM produced switching noise. This can be prevented by switching the valves either ON or OFF for inflation and deflation cycles while using PWM to control the speed of the air pump and therefore control pressure of air in the soft module.

Results shows the suitability and performance of this electronic hardware system when actuating soft robots operating at low pressures (<5 psi). Figure 7 shows the completed system in operation as it actuates a soft robot to produce bending motion. Results obtained from the pressure sensor (Figure 8) shows the pressure of air in the soft module displayed on the LCD. This provides a good measure of the pressurized air in the soft actuator. Figure 9 shows the performance of the designed hardware for different class of soft pneumatic actuators such as the single and multi-channel robots.

The total cost for the whole system including cost of valves, pump, silicon tubes, connectors, pressure sensor and electronic components is within a manageable budget and therefore cost of hardware production is low. In general, the more ambitious the requirements for control are, the higher the costs will be while the system compactness reduces. The higher the required pressure, the larger and costly the solenoid valves will be. The size of the valves is in contradiction to compactness requirements. This also applies to the time taken for the control program to run given the clock speed of the MCU. The extent of compactness is reliant on the degree of integration of control components such as sensors, valves and control logic. For a 2 or more actuator system such as a 5-legged crawling soft robot, the

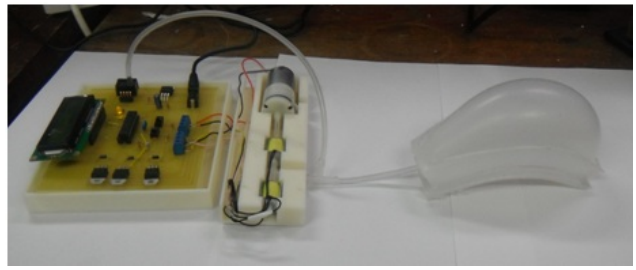

Figure 7. Using the completed system to actuate a silicon soft robot

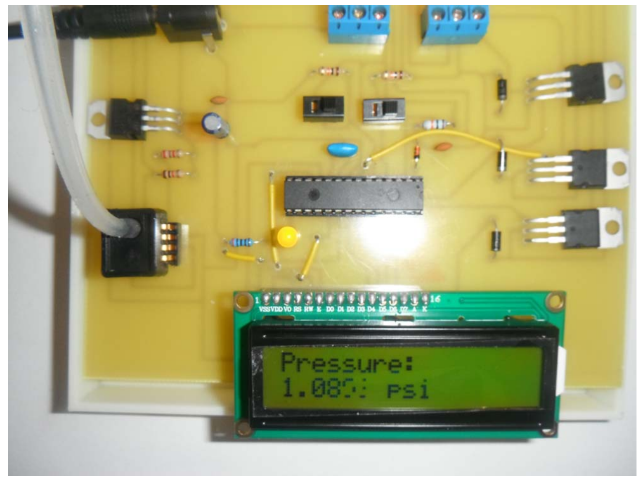

Figure 8. LCD displaying the pressure of air inside the soft actuator

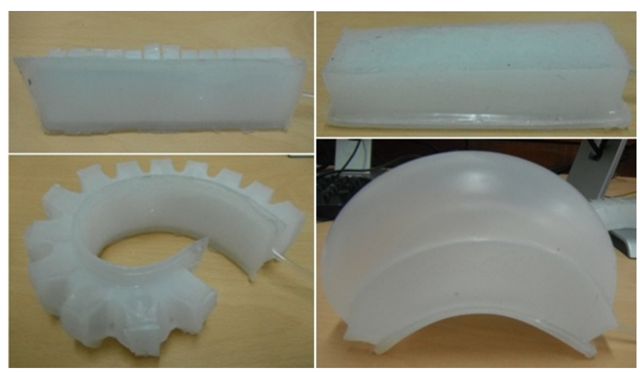

Figure 9. Control hardware used to actuate different classes of soft actuators (before and after inflation)

number of transistors, pressure sensor and solenoid valves increases accordingly. The compactness also depends on the amount of tubing and cables needed for operation.

V. Results

When silicon soft actuators are pressurized, the channel enclosed by soft silicon undergoes high strain and lengthens while the base stiffer layer acts as a constraint, therefore, the expansion generates a bending curvature about the stiffer but extensible layer. To determine the degree of bending

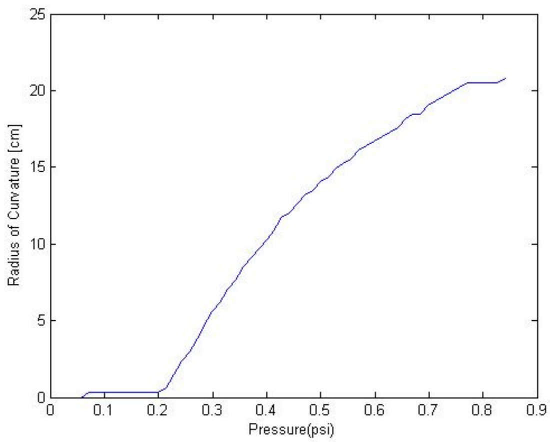

Figure 10. Bending distance as a function of pressure

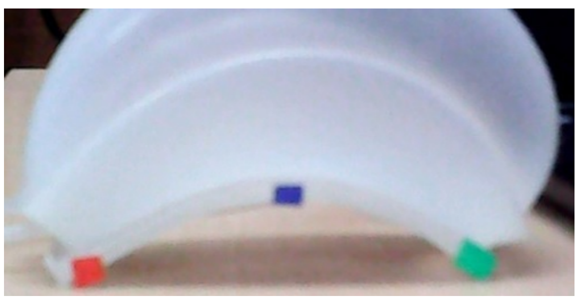

Figure 11. Colour markers used to measure the radius of curvature

that this electronic system can achieve for the one-channel soft robot in Figure 6, a graph of the bending distance as a function of pressure was plotted (Figure 10). The bending distance is defined by the distance between the mid-point of the bottom layer of the soft robot in its uninflated state and the distance of this mid-point when pressurized. To determine this distance, visual processing was performed by using a camera to determine the position of three colour markers as shown in Figure 11. A displacement of 6mm was measured as the distance moved by this soft actuator at the maximum bending. Figure 12 shows that the time taken to inflate the soft robot to its maximum bending is about 10s for the inflation cycle while the deflation time as shown in Figure 13 is about 8s. Factors such as exhaust speed of the valves, power rating of the pump, maximum pressure of valves and pump, length of silicone tubes will affect the time duration of inflation and deflation cycles.

Using the characteristic graph of pressure and radius of curvature of the bending soft actuator to obtain interpolation data, the MCU can then be programmed to approximately set the curvature given a set pressure. For this system, it can be difficult to achieve high accuracy of pressure and curvature measurements. This is due to the accuracy of the control

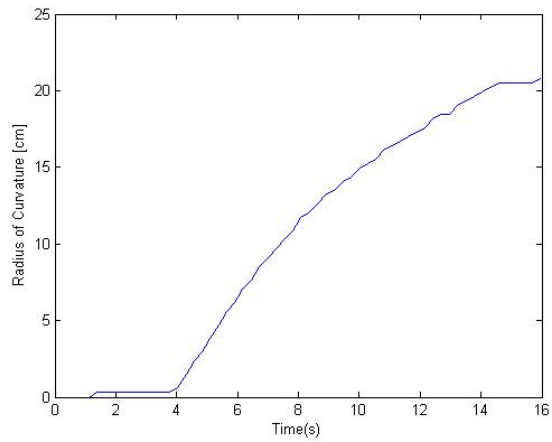

Figure 12. Bending distance as a function of time (inflation cycle)

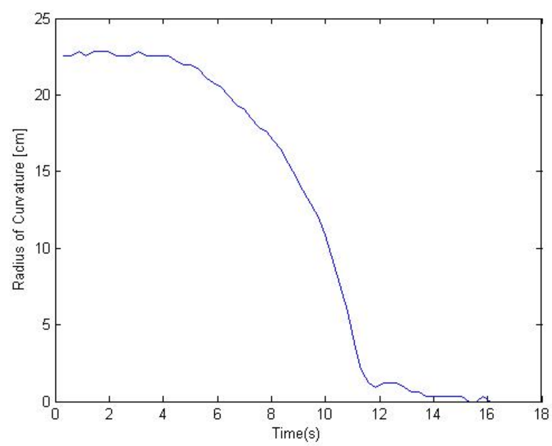

Figure 13. Bending distance as a function of time (Deflation cycle)

and also due to some parameters of the solenoid valve such as leakage and exhaust speed as well as limited curvature measurement accuracy through the use of visual information from a camera. Using a 16-bit ADC to collect pressure data will improve accuracy of pressure measurements. Likewise, an MCU running at a higher clock frequency can be used so that tuning and improved quality of embedded control is realized.

VI. Conclusion

The design of an MCU controlled and operated pressure regulator system to perform actuation of soft robots was presented. An approach to using this embedded system to actuate a single air channel soft robot was demonstrated. The challenges regarding production of a compact electronic circuit for soft robots have been solved. This embedded hardware approach is very promising and can be easily modified to act as a pressure regulator for water by simply

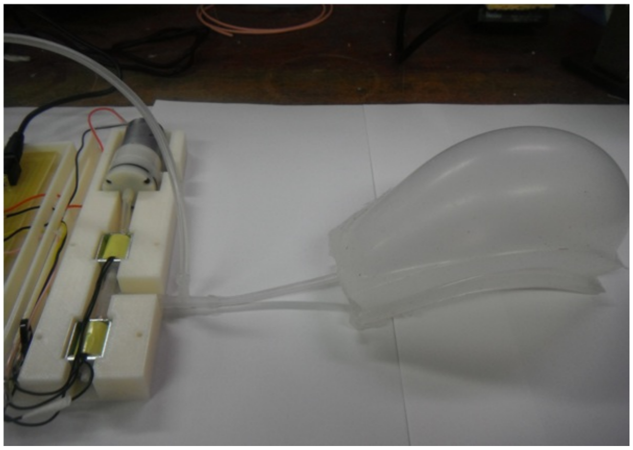

Figure 14. Completed system in operation

replacing the air pump with a water pump and providing suitable valves.

The main limitation of this system is that it can only be used for inflating one continuous air channel. Nevertheless, the system can be easily modified to allow for two, three or more actuators or for McKibbean muscles whereby each muscle will be actuated by 2 solenoid valves. This will also be required in cases requiring 2-joint control necessary for elbow motion or multi-finger actuator where each of the fingers requires a pair of solenoid valves for grasping tasks. For high pressure systems, the air source may be excluded from the board so as to reduce the size and weight, using this approach will allow for the use of an air tank containing compressed air as the pressure source.

The system is modular in terms of mechanical modularity, supply of compressed air, electrical power supply and system integration as all of these are on the PCB board and held in a casing. The control algorithms of this system are relatively simple, it is therefore very easy to modify the computer program to cover a wide range of movements such as crawling, bending, etc required for soft robots. Future research work will include using this hardware system to actuate soft robots designed for neuro-rehabilitation. This design will also be extended to facilitate its use for complex motions as well as for actuating soft robots having more than one pneumatic network.

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