Design of a Soft Robot with Multiple Motion Patterns Using Soft Pneumatic Actuators

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Abstract. Soft robots are made of soft materials and have good flexibility and infinite degrees of freedom in theory. These properties enable soft robots to work in narrow space and adapt to external environment. In this paper, a 2-DOF soft pneumatic actuator is introduced, with two chambers symmetrically distributed on both sides and a jamming cylinder along the axis. Fibers are used to constrain the expansion of the soft actuator. Experiments are carried out to test the performance of the soft actuator, including bending and elongation characteristics. A soft robot is designed and fabricated by connecting four soft pneumatic actuators to a 3D-printed board. The soft robotic system is then established. The pneumatic circuit is built by pumps and solenoid valves. The control system is based on the control board Arduino Mega 2560. Relay modules are used to control valves and pressure sensors are used to measure pressure in the pneumatic circuit. Experiments are conducted to test the performance of the proposed soft robot.

1. Introduction

Robots have been widely used in the fields of industrial manufacturing, agricultural production and medical service. Traditional robots normally consist of rigid modules and can assure the high precision of mechanical motion. However, these robots have limited movement ability in narrow space, which has limited their application in some situations. By comparison, soft robots have low stiffness and high flexibility. They can change their shapes to adapt to the external environment. Due to these advantages, soft robots have wide prospect in application.

Many researchers have paid attention to soft robotics and kinds of soft robots have been developed. Based on the bionics principle, Michael Wehner et al. designed a soft robot, Octobot [1]. It is the first robot with a fully soft body and can move its arms like an octopus. Hernando Leon-Rodriguez et al. proposed a soft micro robot based on the bio-inspired motion of the Amoeba [2]. Ferrofluid material is used to fabricate the robot and external electromagnetic coils are used to actuate and control the soft robot. Hongliang Ren et al. presented a human-compliant body-attached soft robot using four parallel pneumatic soft actuators [3]. The purpose of the soft robotic system is to steer the ultrasound probe cooperatively and replace the manual operation. Nicholas W. Bartlett et al. reported a combustion powered soft robot using 3D-printed techniques [4]. Actuated by the combustion of oxygen and butane, the soft robot is able to jump.

Currently, most soft robots are proposed from the aspect of bionics, e.g. starfish-like soft robots, worm-like soft robots and soft robotic octopus arms [5-7]. New materials, e.g. shape memory alloy (SMA), shape memory polymer (SMP), ionic polymer metal composite (IPMC) and dielectric elastomer (DE), have been used to develop soft robots. Although there are still many challenges to tackle with before wide application of soft robots, new manufacturing technologies and materials have provided fresh ideas for the development of soft robotics.
In this paper, a 2-DOF soft pneumatic actuator is investigated. Based on the proposed soft actuator, a soft robotic system is designed, including actuation system and control system. Experiments are carried out to test the performance of the soft actuator and the soft robot.

2. Design of soft robot

2.1. Soft actuator
The soft actuator includes four parts, a flexible body, a jamming cylinder, two chambers and fibers. The flexible body is made of Ecoflex 0030, a kind of soft materials. The structure of the soft actuator is illustrated in figure 1. The flexible body has two chambers on opposite sides. When one chamber is pressured, the soft actuator will bend to the opposite side. When both two chambers are actuated, the soft actuator will extend along the axis. Along the axis is a jamming cylinder, a membrane with coarse coffee inside. When it is vacuumed, the stiffness of the cylinder will increase. Kevlar fibers on the outer surface of the flexible body can limit inflation in case that balloon effect occurs.

![Figure 1. Structure of soft actuator.]

2.2. Soft robot
The soft robot is shown in figure 2. The proposed soft robot has four legs. Four soft actuators are connected to a 3D-printed board. The distance between two adjacent soft actuators is 70mm. By controlling the bending state of four actuators, the soft robot can complete different tasks, e.g. grasping and walking.

![Figure 2. Soft robot.]

3. Design of soft robotic system
As shown in figure 3, the soft robot system includes two parts, actuation section and control section. The actuation section contains the soft robot, solenoid valves, pumps, regulation boards and a DC power. The control section is designed based on Arduino Mega 2560, including host PC, Arduino board, relay modules and pressure sensors.

Each air channel is connected to the air pump or the vacuum pump via a 3/2 solenoid valve and a 2/2 solenoid valve. Regulation boards are used to control gas flow. By controlling solenoid valves, each channel can be actuated, released or be kept in the current state. Therefore, the motion of the soft robot can be controlled.
Figure 3. Schematic diagram of soft robotic system.

The user interface on host PC is developed by Matlab GUI and Matlab Arduino Support Package is used to establish communication between host PC and Arduino board. Through user interface, users can send commands to Arduino board from host PC. Thus, relay modules can be controlled to control the motion of the soft robot. Arduino board also collects data from pressure sensors. After processing, pressure values of air channels are displayed on the user interface. Figure 4 shows the soft robot experiment platform.

Figure 4. Soft robot experiment platform.
4. Experiments

4.1. Characteristics of soft actuator

The characteristics of the soft actuator have a direct impact on the performance of the soft robot. The motion of a soft actuator consists of bending and elongation, so it is important to understand these characteristics.

The soft actuator will bend or extend along the axis when it is actuated. As figure 5 shows, the bending angle of the soft actuator is defined as the angle between the central axis of the end surface and the central axis of the fixed end. When one chamber is actuated, the soft actuator will bend. The relationship between bending angle and air pressure is shown in figure 6. The bending angle will increase with the increase of air pressure. When the jamming cylinder is jammed, the stiffness of the soft actuator will increase. And the bending angle is smaller than that of unjammed status. The bending angle becomes more sensitive to pressure in high pressure region since the wall thickness of the flexible body decreases as the pressure increases.

When two chambers are actuated simultaneously, the soft actuator will be elongated in the central axis direction. Figure 7 shows the states of the actuator before and after it is actuated. The relationship between elongation and pressure in two chambers is shown in figure 8. The extension length increases with the increase of pressure. The elongation becomes more sensitive to pressure in high pressure region. This is because the cross-sectional area becomes smaller. When the jamming cylinder is vacuumed, the extension length is smaller than that of normal status under the same pressure. This indicates that jammed status can increase the stiffness of the soft actuator.
4.2. Grasping experiment
By controlling the states of chambers in each actuator, the proposed soft robot can work as a gripper. As shown in figure 9(a), when four chambers along the outside are actuated, four actuators will bend to the inside and an object can be grasped from its external surface. Instead, an object can be grabbed from the inner surface when four chambers on the inside are actuated in the way shown in figure 9(b).

![Actuation method](image)

Figure 9. Actuation method.

Objects of different shapes and sizes are used to test the performance of the gripper. Experimental results are shown in figure 10. Grasping modes can be classified into three types. As shown in figure 10(a) and (b), the tip of each actuator will be used to fetch small objects. For medium size objects, both the side surface and the tip of the actuator will contact the object, as shown in figure 10(c) and (d). Figure 10(e) and (f) illustrate the way to grasp objects with large external dimensions. The gripper can pick up these objects by contacting with their inner surfaces.

![Grasping experiment](image)

Figure 10. Grasping experiment.

4.3. Walking experiment
Soft actuators are the legs of the soft robot. By controlling the action order and the status of actuators, the four-legged soft robot can walk on a horizontal surface. As shown in figure 11, a walking circle contains following steps:

- One chamber in leg A and one chamber in leg C are actuated. Leg A and leg C will bend, and the soft robot will move forward.
- All the chambers in leg B and leg D are actuated and chambers in leg A and leg C are released. Leg B and leg D will extend, and leg A and leg C will recover to normal state.
- Leg B and Leg D are released and will recover to normal state.
- One chamber in leg B and one chamber in leg D are actuated. Leg B and leg D will bend, and the soft robot will move forward.
- All the chambers in leg A and leg C are actuated and chambers in leg B and leg D are released. Leg A and leg C will extend, and leg B and leg D will recover to normal state.
- Leg A and Leg C are released and will recover to normal state.

Thus, the soft robot completes a walking circle.

![Actuation method of a walking circle](image)

Figure 11. Actuation method of a walking circle.
When four soft pneumatic actuators are actuated in the way shown in figure 11, the soft robot can walk on a horizontal surface. Figure 12 shows a waking circle of the soft robot. The experimental results show that soft actuators have good controllability. The robot can complete preconcerted tasks and walk as expected. The step length of the soft robot is about 35mm.

Figure 12. Walking experiment.

5. Conclusion

In this paper, a soft pneumatic actuator with two chambers and a jamming cylinder is introduced. A soft robotic system is developed based on this soft actuator and Arduino board. The soft robot is made of four soft actuators. Four soft actuators are distributed at four corners of a 3D-printed board. Experiments show that the soft pneumatic actuator has good flexibility and controllability. Elongation and bending degree of the soft actuator increase with the pressure and are more sensitive to the change of pressure in high pressure region. When the jamming cylinder along the axis is vacuumed, the stiffness of the soft actuator will increase. By controlling the pressure in each chamber, the proposed soft robot can grasp objects and walk. It can grasp objects of different sizes and its walking step length is about 35mm.

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Acknowledgments

This research was financially supported by the State Key Laboratory of Robotics and System, Harbin Institute of Technology under Grant No. SKLRS201501A03.