Lecture Notes in Computer Science: An antagonistic actuation technique for simultaneous stiffness and position control

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Abstract. The application of soft robots can result in significant improvements within a number of areas where traditional robots are currently deployed. However, a challenging task when creating soft robots is to exert effective forces. This paper proposes to combine pneumatic and tendon-driven actuation mechanisms in an entirely soft outer sleeve realising a hybrid actuation principle, to realise a new type of robotic manipulator that can collapse entirely, extend along its main axis, bend along its main axis and vary its stiffness. The created robot arm is inherently flexible manufactured from sections that consist of an internal stretchable, air-tight balloon and an outer, non-stretchable sleeve preventing extension beyond a maximum volume. Tendons connected to the distal ends of the robot sections run along the outer sleeve allowing each section to bend in one direction when pulled. The results from our study show the capabilities of such a robot and the main advantages of the proposed technique compared to traditional, single-actuation type robot manipulators.

Keywords: soft robot, bio-inspiration, hybrid actuation, stiffness controllability

1 Introduction

Taking inspiration from nature, researchers have created new robotic systems to overcome limitations of traditional robots composed of rigid joints and links [4]. In particular, animals' appendages such as the elephant trunk or the octopus arm have become the focus of studies creating soft, hyper-redundant robots and aiming to achieve similar capabilities as their role models [7, 9, 17, 19, 27, 28, 30]. The application of these type of robots can result in significant improvements within a number of fields (such as navigation and manipulation in unstructured environments) where traditional robots are currently deployed [10, 11, 20]. However, a challenging task when creating soft robots is to exert effective forces [13].

In recent years, researchers have investigated several solutions to the complex problem to change and control the stiffness of soft manipulators. A silicone-based, pneumatically actuated soft robot arm has been developed as part of the EU-funded project STIFF-FLOP. STIFF-FLOP focuses on exploring the mechanisms of the octopus and attempts to extract relevant biological features to develop medical robotic systems for Minimally Invasive Surgery (MIS) [14] with integrated sensors [22, 23, 25, 31, 32]. One segment of the current multi-segment manipulator prototype is equipped with three compressible chambers [8, 24]. Stiffness variation is realised with an additional chamber within the silicone body filled with granular that can be jammed by applying a vacuum [13, 14, 18]. Hence, the control of the stiffness of the robot's body is achieved by extending the overall robot system through the introduction of an additional type of actuator. The concept of polymeric artificial muscles described in [5] to actuate a robot manipulator was furthered in [15] by integrating granule-filled chambers which when exposed to varying degrees of vacuum could actuate, soften and stiffen the manipulator's joints. A similar concept is proposed in [16]. A hollow snake-like manipulator consists of multiple overlapping layers of thin Mylar film. By applying vacuum pressure, the friction between the film layers increases which results in a tunable stiffness capability. In [6], the authors report on a thermally tunable composite for mechanical structures. This flexible open-cell foam coated in wax can change stiffness, strength, and volume. Altering between a stiff and soft state and vice versa introduces a time delay as the material does not instantly react to the heating-up or cooling-down process.

In this paper, we propose to combine pneumatic and tendon-driven actuation mechanisms in an entirely soft outer sleeve. The hybrid actuation mechanism and design of the manipulator result in a new type of robotic manipulator that can collapse entirely, extend and bend along its main axis, and vary its stiffness simultaneously. The robot arm is inherently flexible manufactured from sections that consist of an internal stretchable, air-tight balloon and an outer, non-stretchable sleeve preventing extension beyond a maximum volume. Tendons connected to the distal ends of the robot sections run along the outer sleeve allowing each section to bend in one direction when pulled. The results from our study show the capabilities of such a robot and the main advantages of the proposed technique compared to traditional, single-actuation type robot manipulators.
In Section 2, the antagonistic actuation principle is described and the scientific contributions of this paper are summarised. The mechanical design of the soft, stiffness-controllable robot arm is presented in Section 3 along with the overall control architecture. Sections 4 and 5 introduce the experimental setup to validate the tunable stiffness mechanism and present the achievements. The achievements are concluded in Section 6.

2 Contributions of the antagonistic actuation principle

The role model for our work is the octopus [12, 17]. Its soft arms virtually have an infinite number of Degrees of Freedom (DoFs). Studies by biologists show that the octopus arm has longitudinal and transversal muscles. Both sets of muscles can be activated in an antagonistic way so that it is possible for the octopus to control the stiffness of parts of its arm. This natural feature enables the octopus to catch fish, crawl across the seabed, or move obstacles.
We have here transferred the natural antagonistic principle of the longitudinal and transversal muscles into an antagonistic robotic actuation system. Our robot manipulator makes use of two fundamental actuation means - intrinsic, pneumatic actuation and extrinsic, tendon-based actuation - able to oppose each other. This cooperative hybrid system is capable of varying the arm's stiffness over a wide range combining the advantages of extrinsic and intrinsic actuation mechanisms at the same time [3]:

- Tendons are utilised to operate manipulators with a high payload due to high tensile strength [21].
- Due to the thin structure of tendons and the externally placed motors used to control the length of the tendons, tendon-driven manipulators can be easily miniaturised [1].
- Controlling the tip's position and orientation of tendon-actuated manipulators is fairly accurate [2].
- The payload of a tendon-driven robot depends on the tensile strength of the tendons and the maximum force that can be generated by the applied electrical drives.
- Pneumatically actuated manipulators are inherently compliant and suitable to share the working environment with humans [5, 26].

Fusing these two sets of actuation mechanisms allows us creating a manipulation with enhanced capabilities above single-type actuation robots [29]. Hence, the significant contributions made by the creation of the actuation mechanism are as follows:

- The implementation of the hybrid actuation system together with the structure of the robot allows the manipulator to transform between being entirely shrunk and completely elongated. We are able to achieve an extension of factor 20 or more.
- The antagonistic actuation mechanism allows the manipulator to transform between a soft and stiff state: This can be achieved by inflating the robot and fastening the tendons at the same time. This collaborative principle results in a continuous stiffness controllability.
- Our developed robot has no backbone and a simple structure made of soft material such as fabric and latex. Hence, the manipulator can be miniaturised easily and squeezed through narrow openings being still fully functional.

3 Mechanical structure and design

3.1 Structure and Assembly of the Manipulator

A CAD drawing of the manipulator's structure is shown in Fig. 1. The structure of the prototype consists of three parts:

- The inner air-tight latex bladder is stretchable. The pneumatic actuation system is connected to the base of the bladder.
- The outer polyester fabric sleeve is non-stretchable but shrinkable. This sleeve restricts the expansion of the inner bladder when pressurised.
- Two sets of three nylon tendons are fixed at the tip and in the middle of the manipulator dividing the robot into two sections.

The cylindrical polyester sleeve is slipped over the latex bladder. The length of the inflated soft robot is 20 cm; the diameter is 23 mm. As mentioned earlier, the non-stretchable fabric material limits the expansion of the inner sleeve and prevents any ballooning in radial direction beyond the maximum diameter of 23 mm. Hence, the manipulator can only expand along its longitudinal axis (elongation) to a maximum length of 20 cm. In order to avoid the inner latex sleeve from being twisted whilst changing between an inflated and deflated state, the tip of the latex bladder and fabric sleeve are connected. Two sets of three tendons are inserted into guidance channels in the periphery of the manipulator along the outside of the polyester sleeve. These channels are spaced 120°

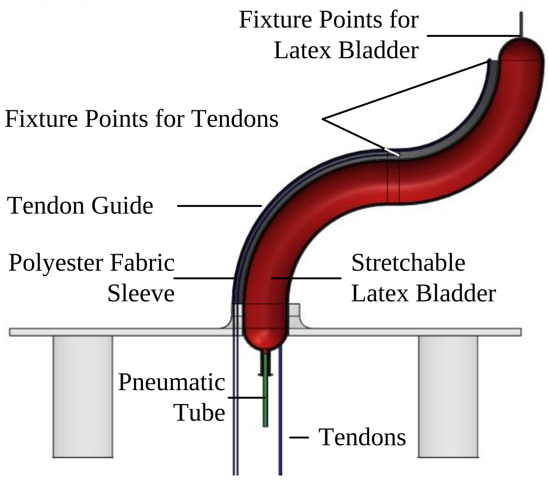

Fig. 1. The prototype of the manipulator consists of an inner air-tight, stretchable latex bladder, an outer, non-stretchable (but shrinkable) polyester fabric sleeve and three pairs of nylon tendons. The latex bladder is pneumatically inflated or deflated. The tendons are mounted on the outside at tip and in the middle of the manipulator allowing to control the robot's configuration [28].

apart. In our two-section prototype, three tendons are fixed to the tip of the manipulator and another set of three tendons are attached to the tip of the proximal section (i.e., the middle of the manipulator). Employing this approach, the robot's two sections can be independently controlled (see Figs. 1 and 2). Adjusting the length of the tendons appropriately also controls the stiffness of the arm - e.g., decreasing the tendon length at a given air pressure will reduce the manipulator's length and result in a stiffer state.

3.2 Stiffness and position control architecture

The overall control architecture of the system is shown in Fig. 2. A SMC ITV0010-3BS-Q pressure regulator is utilised to control the air pressure from 0.001 MPa to 0.1 MPa. This pressure range is capable of inflating and deflating the inner latex bladder. Sufficient pressure supply is ensured by a BAMBI MD Range Model

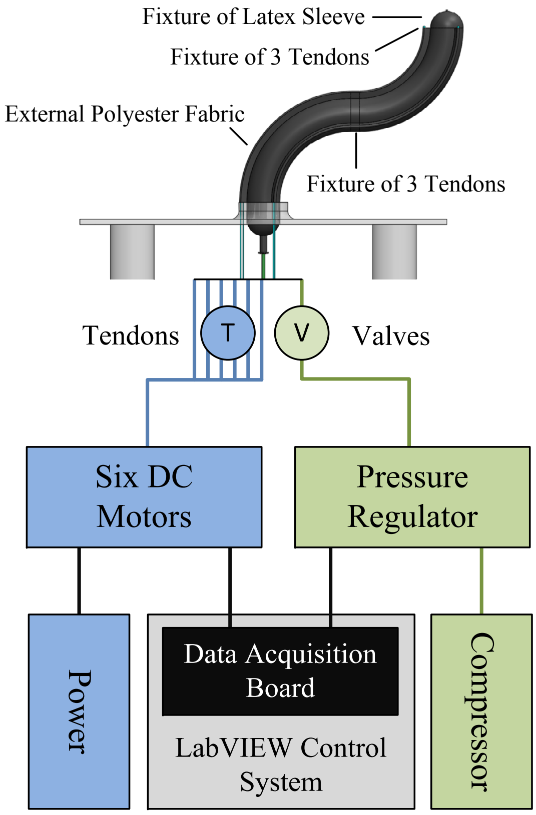

Fig. 2. DC motors (tendon actuation) and a pressure regulator (pneumatic actuation) are interfaced between with a Data Acquisition Board and the bio-inspired manipulator [28].

150/500 air compressor.
Pulley systems are installed and mounted to six Maxon RE-max 24 DC motors. Each pulley has a radius of 6.4 mm. The attached gear (Maxon Planetary Gearhead GP 22 C) provides a torque of up to 2 Nm resulting in a maximum force of 312.5 N considering the pulleys.
The DC motors and pressure regulators are interfaced via an NI USB-6211 DAQ card to LabVIEW software. The hybrid actuation system receives steering commands from a joystick (Logic 3 JS282 PC Joystick): The toggle controls the angular position of the shaft drives which drive the tendon pulleys. The pulleys decrease or increase the length of the tendons resulting in bending of the manipulator. A button is integrated to regulate the air pressure inside the latex sleeve. Being able to steer the manipulator using the tendons and regulating the pressure at the same time allows keeping constant pressure when the deflatable arm shrinks, extends or bends on the one hand and to control the stiffness (increasing the pressure in the latex bladder) when pulling all tendons simultaneously on the other hand. In this way, a motion control architecture was implemented in order to conduct the experiments in Section 4.

4 Experimental test setup

In order to validate the manipulator's performance of changing stiffness, experiments have been conducted applying lateral forces $\boldsymbol{F}_x$ to the manipulator. Fig. 3 gives a top view of the overall experimental setup. The experiments consisted of loading and unloading the manipulator up to a 15 mm deflection. An ATI Nano17 Force/Torque sensor was mounted on a motorised linear module to monitor the stiffness variation. The motorised linear module was running at a speed of 0.25 $\frac{\text{mm}}{\text{s}}$. The unloading phases are identical to the loading phases, with the exception that the module is moving in the opposite direction to its initial position. Forces were applied at two different locations while the tendons were

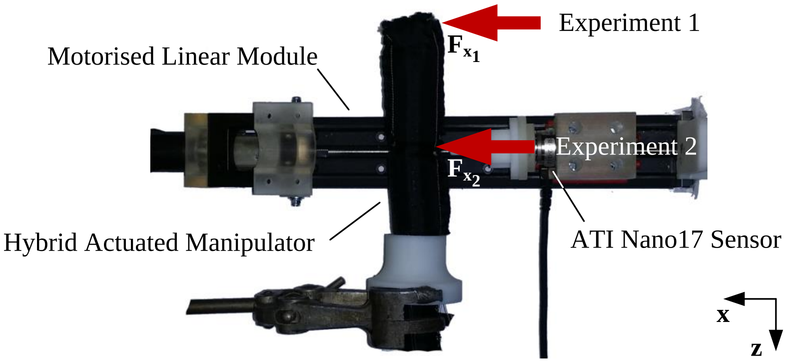

Fig. 3. Overview of the experimental setup to validate variable stiffness with a ATI Nano17 Force/Torque sensor and a motorised linear module [28].

not actuated by the pulleys in order to evaluate the stiffness variation in a static condition.
Data from the force sensor and the linear module were recorded at 1 kHz using a DAQ card (NI USB-6211). Four trials were performed for each deflection location, and with the average and variability of each point plotted against the deflection distance. The results are reported in Section 5.1 and 5.2 respectively.

5 Results

5.1 Lateral Forces (Experiment 1 and 2)

Measuring forces during the loading and unloading process of Experiments 1 and 2 are displayed in Figs. 4 and 5. The curves showing load forces (or forward motions) of the manipulator start in the origin of the coordinate frame $(0, 0)$ for all figures.
In Experiment 1, a displacement of 15 mm was applied to the manipulator's tip. The lateral forces $\boldsymbol{F}_{x_1}$ were recorded and can be seen in Fig. 4. In Fig. 4(a), the manipulator's internal bladder had a constant pressure of 0.0075 MPa; a pressure of 0.015 MPa was recorded in Fig. 4(b). From the graphs, the manipulator with lower pressure exhibited a fairly linear profile, reaching a peak of 0.9 N. When the pressure was increased to a higher value, the robot displayed a non-linear behaviour during the displacements test, reaching a maximum force $\boldsymbol{F}_{x_1}$ of 1.4 N. The hysteresis and average variability were significantly lower when applying a higher pressure.
Fig. 5 show the results of Experiment 2. Here, a lateral force $\boldsymbol{F}_{x_2}$ was recorded when deflecting the center of the manipulator. From Fig. 4(a), the maximum

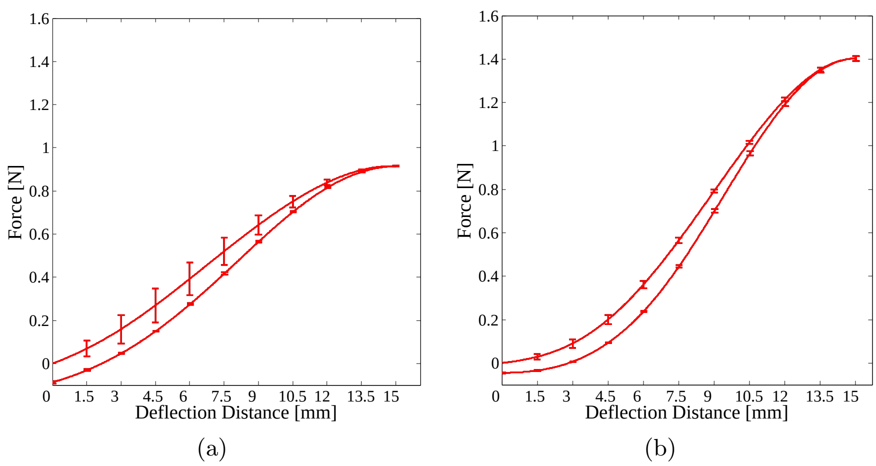

Fig. 4. Deflection versus force at the manipulator tip ($\boldsymbol{F}_{x_1}$) for pressures of (a) 0.0075 MPa and (b) 0.015 MPa [28].

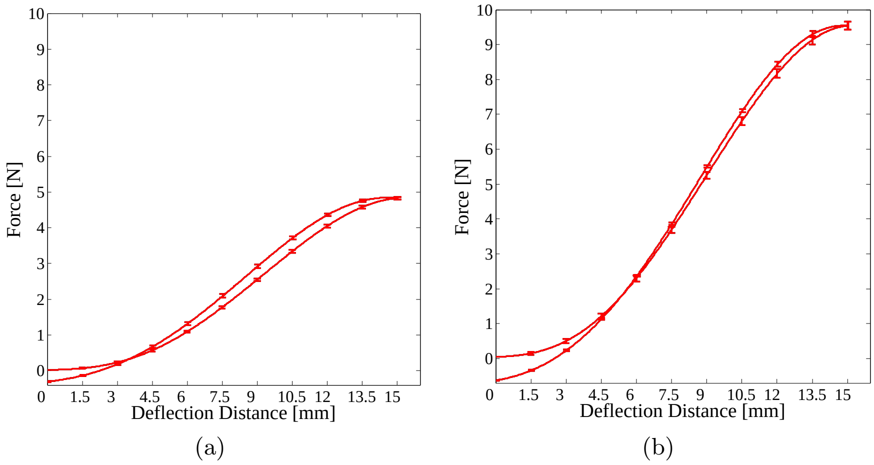

Fig. 5. Deflection versus force at the center of the manipulator ($\boldsymbol{F}_{x_2}$) for pressures of (a) 0.0075 MPa and (b) 0.015 MPa [28].

force achieved is 4.8 N for a pressure of 0.0075 MPa. When raising the value to 0.015 MPa, a force of 9.5 N was measured. Similar to the results of Experiment 2, the hysteresis is lower for a stiffer manipulator.

From Experiments 1 and 2, it can be noted that the amount of lateral force increases and the hysteresis decreases with higher pressures applied to the latex bladder during deflections.

5.2 Bending Behaviour

In order to show the working space and bending behaviour, experiments have been conducted actuating the tendons that are fixed at the tip and middle section of the manipulator. The results were captured for robot movements in one plane as shown in Fig. 6. In both figures, the manipulator is actuated by one pulley attached with a velocity of approximately 1 $\frac{\mathrm{mm}}{\mathrm{s}}$. In Fig. 6(a), movements are shown that result from the actuation of one tendon fixed in the middle of the manipulator. In this case, only the bottom section bends (up to 90 °); while the top section remains straight. Fig. 6(b) shows the actuation of one tendon attached to the manipulator tip. The pulling force leads to a bending behaviour of both sections at the same time changing the tip orientation by 180 °. In both bending experiments, the internal pressure was set to 0.015 MPa and remained constant. Hence, an infinite range of bending configurations can be achieved combining simultaneous actuation of the three tendons and different level of internal pressure.

Fig. 6. Single tendon actuation of the (a) bottom section and (b) top section [28].

6 Conclusions

We present here a new hybrid and antagonistic actuation system for a robotic manipulator fusing pneumatic with tendon-driven actuation. Being inspired by the biological role model, the octopus, our antagonistic actuation system aims at modeling the octopus' way of using its longitudinal and transversal muscles in its arms: activating both types of muscles, the octopus can achieve a stiffening of its arms.

Our concept goes beyond state-of-the-art in the field of soft robotics: our robot is mainly made of thin sleeve-like components filled with air to achieve a fully-extended state, and thus can be shrunk to a considerably small size when entirely deflated. This capability to move between these two extreme states make the robot a particularly useful candidate for applications such as Minimally Invasive Surgery or search and rescue. Our experimental study shows that the our manipulators, indeed, is capable to bend, to morph from entirely inflated to completely shrunk as well as to squeeze through narrow openings.

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