A new bio-inspired, antagonistically actuated and stiffness controllable manipulator

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I. INTRODUCTION

Robotic manipulators can be divided into different classes, including discrete, serpentine and continuum robots [1]. Most robots in use today have a number of discrete and usually rigid links connected by simple joints. Our work though has been inspired by biology [2], [3] - specifically by the octopus, with its soft tentacles and virtually infinite number of degrees of freedom (DoFs). Biological studies show that the octopus is capable of actuating the different types of muscles in such a way that it can control the stiffness of its arms, enabling the animal to catch fish, move stones or even walk across the seabed. Taking inspiration from the antagonistic behaviour of octopus arms, our robot manipulator makes use of two fundamental actuation means, pneumatic actuation and tendon-based actuation, able to oppose each other and thus capable of varying the arms' stiffness over a wide range. Our robot arm can be said to employ two main actuation mechanisms in a hybrid fashion - intrinsic (pneumatics in our case) and extrinsic (tendon actuation in our case) [1], [4].

As it is the case for other robots developed recently, we use extrinsic actuation based on tendons to achieve bending away from the longitudinal axis of the robot arm. Tendons that are attached at the tip and intermediate points of the arm are pulled by externally situated motors controling the length of each tendon see e.g. Intuitive. The overall DoF depends on the number of integrated tendons and fix points along the manipulator [5]. Other manipulators whose links are moved by tendons are [6]–[10]. Most tendon-driven robot manipulators cannot lengthen or shorten their structure longitudinally [11], [12].

While most current robot arms make use of only one type of actuator such as tendons or motors integrated with the robot joints, our robot arm employs two actuation mechanisms. The tendon based mechanism is combined with pneumatic actuators to allow for antagonistic control. The pneumatic actuation which can be considered intrinsic actuation provides our arm mainly with extension capability. Other robot arms that are entirely based on pneumatic actuation have been developed in the past. One example of an intrinsic pneumatic actuation principle employed in a robot arm is the Octarm manipulator equipped with a set of McKibben actuators connected in series and in parallel [13]. Another example is the universal joint based robot for minimally invasive surgery (MIS) [14]; each finger-like segment is driven by 7 micro-motors leading to a miniaturized manipulator arm with an outer diameter of 12 mm. Another robot arm that is actuated pneumatically is the soft robot arm 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 robotics systems for MIS [15] with integrated sensors [16]–[18]. The STIFF-FLOP robot arm is made up of silicon segments with each segment being equipped with a set of parallel compressible chambers; the current prototype consists of two segments arranged in series [19].
Stiffness variation can be realised with an additional chamber within the silicone body filled with granular that can be jammed by applying a vacuum [20]. 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 proposed in [21] to actuate a robot manipulator was furthered in [22] by integrating granule-filled chambers which when exposed to

(a) (b)

Fig. 1. Prototype of the new bio-inspired, antagonistically actuated and stiffness controllable manipulator in the (a) stiff and elongated and (b) entirely shrunk state.

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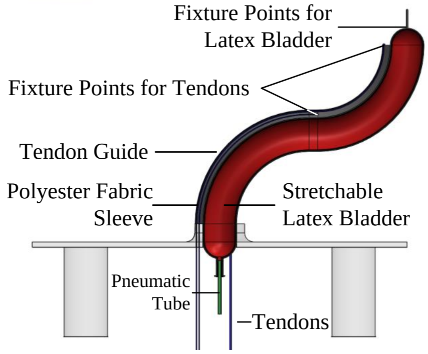

Fig. 2. Section view of the manipulator's structure.

varying degrees of vacuum could actuate, soften and stiffen the manipulator's joints.

Appropriately fusing two different actuation mechanism often allows enhanced manipulation capabilities above single-type actuation approaches [4] - enhanced control of the manipulator's configuration, stiffness and compliance can be observed. Such a hybrid robot concept is the one described in [23]; the authors created a system where pneumatic actuators are combined with an electro-mechanical actuation mechanism. Also, the work by Immegal [24] aims at bringing together extrinsically and intrinsically actuation principles. The idea of fusing pneumatic and tendon-driven actuation was also explored in [25] - in their work, each robot segment is made up of a pressurizable inner hose inside a surrounding hose and a set of cables attached to aluminum plates at the top and base of each of the many segments.

Here, we propose to fuse pneumatic and tendon-driven actuation mechanisms in an entirely soft outer sleeve realising a hybrid actuation mechanism, to realize a new type of robotic manipulator that can collapse entirely, extend along its main axis, bend along the main axis and vary its stiffness. The proposed robot arm is inherently flexible manufactured from segments 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 segments run along the outer sleeve allowing each segment to bend in one direction when pulled. The developed robot arm is depicted in Figure 1. The results from our study show the capabilities of such a robot and the main advantages of the proposed technique when compared to traditional, single-actuation type robot manipulators.

II. DESIGN OF THE HYBRID ACTUATION MECHANISM

A. Structure and Assembly of the Manipulator

A section view of the robot arm is depicted in Figure 2. There are three main parts that make up the overall robot structure: an inner stretchable air chamber, an outer, non-stretchable (but compactable) fabric sleeve and triplets of nylon tendons per each of the two segments. The outer sleeve is 20 cm in length and has a diameter of 23 mm, when fully inflated. Since the outer fabric cannot stretch, the outer sleeve keeps the inner balloon from extending indefinitely and restricts it in radial direction to a maximum diameter of 23 mm. During transition from complete deflation to maximum inflation, the manipulator is capable only of extending along its main axis (translational extension). The manipulator stiffness is varied by changing the tendon length - hence, pulling the tendons in at a certain air volume, the outer sleeve will shorten, whilst increasing its stiffness, and vice versa.

In our robot, the extrinsic actuators, i.e. the tendons are guided through specific fabric channels on the outside of the manipulator sleeve, 120° apart along the circumference of the robot's cylindrical body. In our two-segment experimental system, a triplet of tendons are attached to the distal end of the manipulator and another tendon triplet connected the mid-section of the robot - hence, the two segments of our manipulator can be actuated individually, Figures 2 and 3.

B. Active Motion Control Setup

Figure 3 shows the setup of the entire robotic system. A pressure regulator (SMC ITV0010-3BS-Q) is used to control the air pressure in inner balloon from 0.001 MPa to 0.1 MPa, allowing the controlled inflation and deflation of the balloon. An air compressor (BAMBI MD Range Model 150/500) is employed to provide the required pressure.
The tendons are operated via a pulley system of a 6.4 mm radius driven by DC motors (Maxon RE-max 24) via a gear (Maxon Planetary Gearhead GP 22 C), allowing us to apply a torque of up to 2 Nm and a force of up to 312.5 N at the outer edge of the used pulleys.

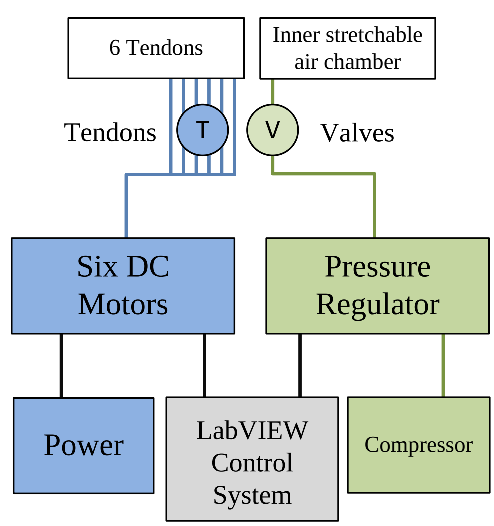

Fig. 3. Active motion control architecture involving tendon and pneumatic actuation.

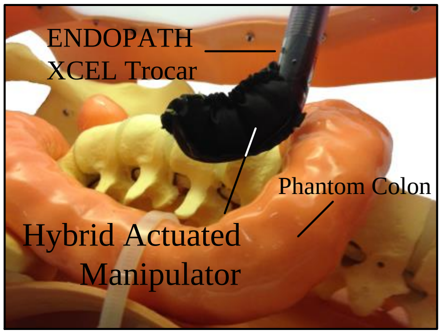

Fig. 4. The manipulator is squeezed through an ENDOPATH XCEL Trocar (18 mm diameter) and actuated.

A DAQ card (NI USB-6211) and LabVIEW software are used to control the motors and pressure regulators taking input from a joystick (Logic 3 JS282 PC Joystick) for remote control of the overall system. In addition, a button is used to regulate the pressure inside the robot's air chamber. In the conducted experiments, we used the joystick to control the tendons and thus steer the manipulator whilst keeping the pressure in the balloon constant. Thus, most of our experiments allowed controlling the robot's motion whilst keeping the pressure and, hence, stiffness, constant - see [26].

III. DISCUSSION AND 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 MIS 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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