How to Create Self-Sensing Air Muscles from Conductive Fibers

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***Abstract*— By constructing Mckibben Muscles out of conductive fibers, we are able to measure the contraction and force output of the muscle without external encoders. These self-sensing actuators can then be controlled in flexible structures, without the rigid, well-defined joints demanded by typical position encoders. The contraction is manifest in changes in the inductance of the braid. The force output is detected through changes in the braid resistance due to strain in the conductive individual fibers.**

I. INTRODUCTION

Pneumatic Artificial Muscles (PAMs) represent a popular class of actuators for soft robotic systems. Trivedi et al. record numerous examples of these actuators in soft manipulators and swimming robots [1]. They are naturally compliant can produce force magnitudes greater than animal muscle [2]. In traditional applications, PAMs are necessarily combined with external encoders to record their contraction state. The trunk-like manipulator OctArm VI, for example, requires nine, draw wire strain sensors mounted at the base to approximate its shape for feedback [3]. However, The volume required for the encoders precludes the ability to observe all the degrees of freedom. Additionally, these encoders are vulnerable to damage from the environment and could not be used swimming robots without careful sealing [4]. Moreover, the shape of a soft manipulator can change dramatically from forces applied along the length of the manipulator. Force sensors placed at the base are unable to distinguish between tip loads and distributed loads [1]. The force output of PAMs is typically predicted using measurements of internal pressure in experimentally derived models. To know the force output by each actuator by this method, each muscle would need a pressure transducer.

Our method allows each PAM to record its own force output and contraction state by measuring the changes in the conductive wires that form the braid. Force measurements come from the changes in resistance due to internal strain. Contraction measurements come from changing inductance due changes in the alignment and proximity of the fibers.

II. THEORY

Our unique PAM construction uses conductive fibers electrically connected in single circuit. These fibers form the braided sheath that surrounds the flexible inner tube. The fibers are connected so that the current rotates about the long axis of the muscle in a consistent direction. This creates a magnetic field similar to the field from a solenoid. The self-inductance of the circuit increases as the fibers to become more aligned and closer together during contraction. The resistance of the wires changes as they are subjected to the stress from the internal pressure and the external forces at the muscle end. Figure 1 illustrates the wiring configuration and changes in electrical properties.

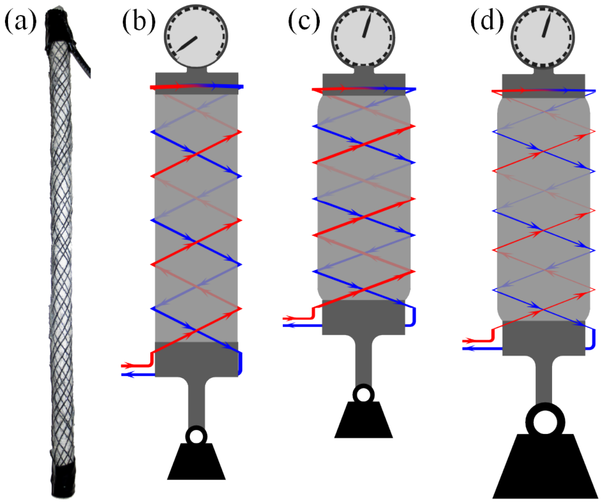

Fig. 1: The braid of the PAM is made from wire connected into a single circuit. (a) a prototype used in our experiments (b) The right handed helices are connected to an adjacent left-handed helix. The current always rotates about the long axis of the muscle in an consistent direction (c) When the muscle contracts, the fibers move closer together and become more aligned (d) End-loads create additional stress in the wires which can be measured via their change in resistance

III. METHODS

To create a reinforcing mesh made of conductive fiber, we wound silicone coated wire around a silicone tube. The layers of wire were then coated in an elastomer to help them maintain their form (because they were not braided like a typical PAM). The elastomer limited the total contraction the muscle was able to undergo. For this reason, we built two prototypes with different winding angles. In their relaxed configurations, one muscle was 29 cm long with an angle between the fibers and the long-axis of the muscle of 20 °. The other muscle was 30 cm long and had a winding angle of 30 °. The inner tube of each muscle had an outer diameter of 9.5 mm. The muscles had eight right-handed and eight left-handed helices forming the reinforcing structure. Their inductance and resistance was characterized with a commer-

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cial LCR meter. A custom test stand was used to apply forces and measure the muscle contractions. Our prototypes were tested at a variety of end-loads with pressures up to 200 kPa. Measurements were taken when the muscle had sufficient pressure to support the end-load.

IV. RESULTS

A. *Sensor Characterization*

The change in inductance for a given end-load was roughly linear over the contraction. Figure 2 shows the results from these tests. The elastomer surrounding the fibers limited the contraction to only 6%. Over the course of this small contraction, the inductance increased by roughly 20% for the 30° muscle and 30% for the 20° muscle.

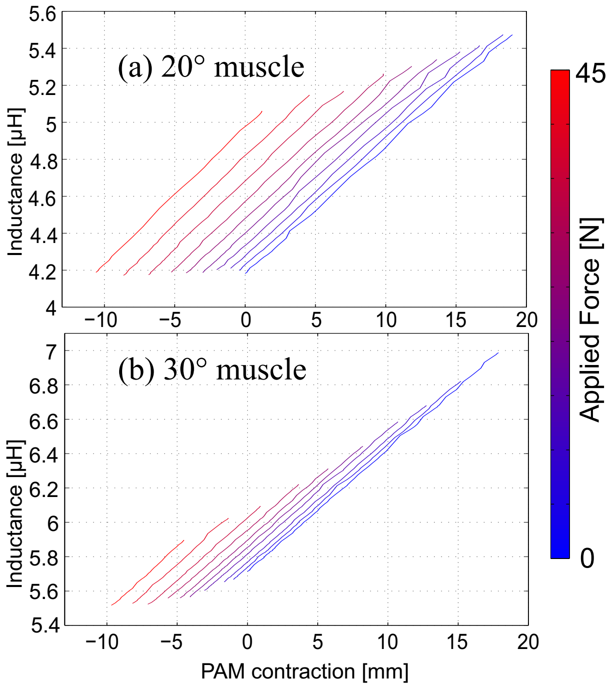

Fig. 2: The inductance to contraction relationship was roughly linear over the range of contractions that we were able to test

B. *Predicting Contraction*

We used the results from our characterization experiments to generate polynomial functions relating the measured resistance and inductance of the braid to the end-load and contraction state. To test this calibration, we applied arbitrary, non-linear loads to the ends of the prototypes using rubber bands. Figure 3 shows the contraction we predicted by our calibratoin versus the contraction we measured by conventional means. Aside from the few erroneous readings from the LCR meter, the calibration appears to be useful for sub-millimeter contraction characterization.

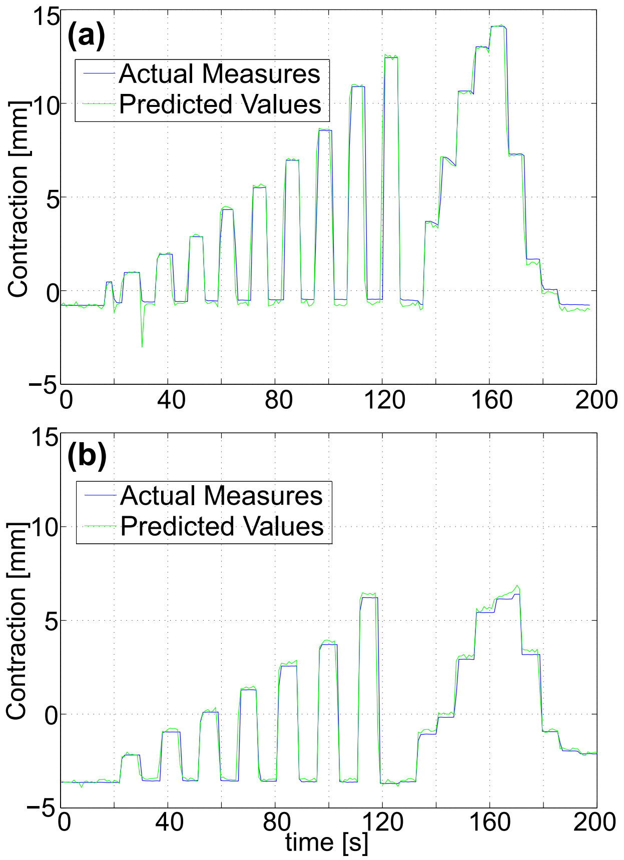

Fig. 3: We are able to very precisely predict contraction, even with arbitrary, non-linear end-loads. The graphs here show the 30° muscle with (a) lower end-load and (b) higher end-load.

V. DISCUSSION

Our method appears to be a promising way of including position and force sensing capabilities into the structure of a PAM. This should enable soft robots to employ PAM actuators without the need for external encoders. Our hope is that this freedom will enable the design of increasingly sophisticated and useful robots.

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