Self-Sensing Pneumatic Artificial Muscles for Feedback Control using the Inductance of "Smart Braids"

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Summary

Measuring and controlling Pneumatic Artificial Muscles (PAMs) without instrumented, mechanical structures can be challenging. This is the case, for example, when the actuators are used in soft, human exosuits [5]. "Smart Braids" measure the length of PAMs through the inductance of a conductive braid. The inductance increases linearly with the contraction of the actuator. We have modeled and tested these self-sensing actuators. We have also tested the performance of Smart Braid sensors as feedback for the control of antagonized actuators.

Introduction

Pneumatic Artificial Muscles (PAMs) are force-dense, contractile actuators. These actuators have been researched for many decades [2] and are commercially available. They are made from an elastomeric tube surrounded by a braided, fiber mesh. The braided mesh is typically made from high-strength polymeric fibers. The mesh converts the pressure from the air in the tube into force along the axis of the actuator.

These actuators have been used extensively in human assistive devices and legged robots [1]. They can be used, for instance, to create lightweight powered ankle-foot orthoses to assist push-off during walking [4]. Their soft nature allows them to create conforming "exosuits" that can assist joint motion without bulky mechanical linkages [5]. In legged robots, the actuators have been used extensively [1]. This comes in part from the high force density and inherent compliance of the actuators [2].

Figure 1 illustrates how a pair of PAM actuators could be arranged with a soft structure to provide assistive torque to the knee. Per their soft nature, PAM actuators do not require rigid mechanical joints. This can enable new kinds of soft assistive devices and robots. Without a rigid mechanical structure with discrete joints, however, it can be difficult to measure and control the motion of the actuator.

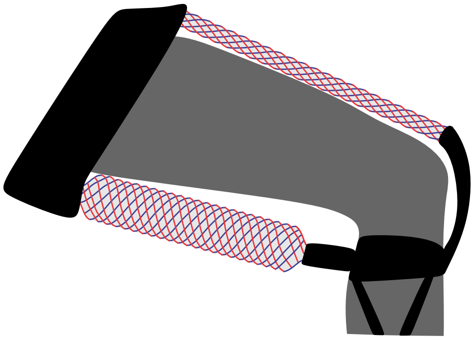

Figure 1: Pneumatic Artifcial Muscles (PAMs) are lightweight and force-dense actuators. They can be used to create soft assistive devices such as the one depicted here [5]. The "Smart Braid' sensors we have developed can measure the the length of the actuators in settings such as this.

It would be valuable if the motion of PAMs could be measured in soft systems. We accomplish this length-measurement through the use of "Smart Braids." Smart Braids are formed from a braid of conductive fibers surrounding the muscle. The braid is made from right-handed and left-handed helices. The fibers are connected so that the current alternates between the hands of the helices, always circling the axis in the same direction. This creates a single, solenoid-like circuit with an inductance that increases with the actuator contraction (Fig. 2). By measuring the inductance of the braid, the length of the actuator can be determined [3].

Methods

The inductance of Smart Braids can be described by analytic and numeric models [3]. These models predict an approximately linear relationship between the actuator contraction and the inductance. Some external circuitry is required to convert the changing values of inductance into a usable signal. For real-time control, we use small "Inductance-to-digital converters." These ICs measure the ringing frequency of an LC oscillator formed by the Smart Braid and a fixed capacitor.

We have tested the performance of Smart Braid

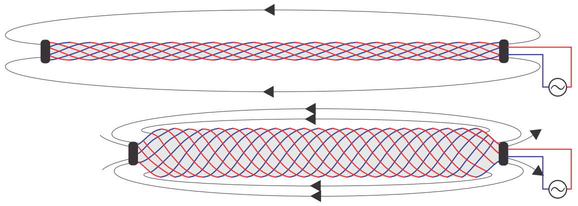

Figure 2: The Smart Braid sensors are formed by wires making up the reinforcing braid of the actuator. The wires form a solenoid-like circuit. The contraction of a Smart Braid PAM leads to an increase in the inductance of the circuit (adapted from [3]).

sensors both on individual actuators and as feedback for the angle control of a rotary joint driven by antagonized PAMs. The results of the single actuator experiments were compared against our models. The performance of the feedback controller was compared against a controller using a traditional encoder. The gains of the controllers were selected with the same, Zeigler-Nichols procedure. The controllers were evaluated on a series of step changes in the reference angle.

Results

As predicted by our models, Smart Braid sensors exhibit a predictable and linear increase in inductance as the length decreases with no appreciable hysteresis [3]. The PAM actuator we tested had a resting length of about 30 cm. The linear calibration of the Smart Braid inductance to length resulted in a sensor accuracy of about 1 mm.

In feedback control, the antagonized Smart Braid PAMs created stable and accurate feedback under dynamic and high-force conditions. As we expected, the controller performance with feedback from a rotary encoder was slightly better than the performance with the Smart Braid sensors. The rotary encoder controller resulted in a 16 % reduction in the RMS of the transient error between the reference angle and the measured angle. The steady-state error of the encoder-based controller was about 50 % smaller than the steady-state error of the inductance-based controller.

Discussion

We have demonstrated that Smart Braid PAMs could be used in place of traditional sensors on soft robotic and assistive devices. Rather than using measurements from sensors attached to discrete mechanical joints, Smart Braid PAMs can measure their own contraction. Essentially, the Smart Braid technology allows PAMs to become soft, force-dense servomotors.

These self-sensing actuators can be fabricated from off-the-shelf parts and low-cost circuitry. The only difference between a traditional PAM and a Smart Braid PAM is in the reinforcing fibers. Smart Braid fibers can be made from high-flex-life wires such as “tinsel wire.” These wires have conductive elements integrated with high-tensile-strength polymer cores. The ICs for measuring inductance are small, low-cost and can provide rapid sampling rates.

The creation of self-sensing PAMs will enable new kinds of assistive devices and legged robots. These systems would not need rigid structures to measure the state of the actuators. This could enable fully-soft, assistive exoskeletons to employ control algorithms based on the users movement. The smart actuators could also enable controllable legged robots to be built from compliant joints or soft structures.

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