Soft Actuators with Integrated Inductance Sensing for Material Robotics

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Many of today's soft robots are controlled in a purely open-loop fashion. While models can given approximate motion prediction under known loading conditions, closed-loop feedback is necessary to control the position of soft robots with unknown loads. The limited availability and capabilities of truly soft sensing systems has motivated the development of new ways of measuring robot motion.

One way to measure the deformation of soft materials or actuators is through the inductance of deforming circuits. These circuits can be designed to exhibit changes inductance as a result of motion in desired directions. For example, the circuits on a bending-bellows-like actuator can be designed to exhibit a greater sensitivity to bending than off-axis twisting [3] (Fig. 1a). Multiple degrees of freedom can be measured by including multiple sensors. For example, the deformation of a two-active-degrees-of-freedom continuum joint can be estimated by measuring the bending in each half of the joint [5]. The inductance-based feedback permitted orientation control with less than 3 ° of average steady-state error.

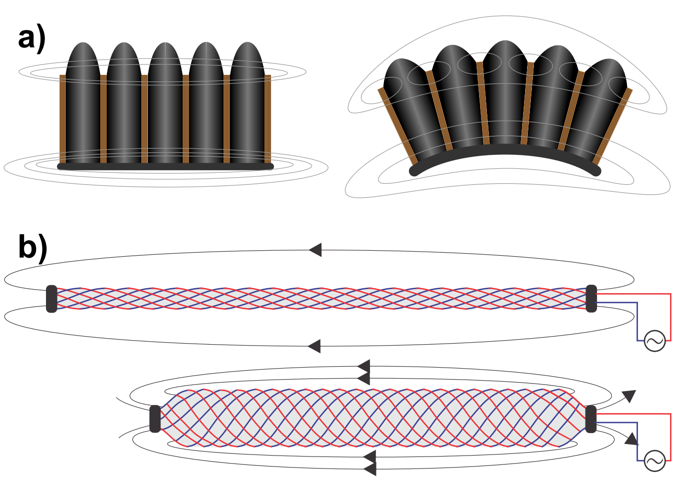

Fig. 1. a) Inductance sensing can be integrated into the structure of a bellows-like actuator by wrapping insulated conductive wire around the minor diameters. The extension of the actuator separates the coils and results in a decrease in their mutual inductance. b) Inductance sensing can also be integrated into Fiber-Reinforced actuators by replacing the typically non-conductive fibers with insulated conductive wire. Shown is a "Smart Braid" McKibben muscle which exhibits an increase in inductance as the actuator contracts. Adapted from [1] and [3].

The conductive wires can also be used in the place of typically non-conductive reinforcing fibers in Mckibben Muscles [1] or other fiber-reinforced actuators [2] (Fig. 1b). By measuring the inductance, the length of the actuator can be estimated. For contracting McKibben muscles, the inductance response is precise, linear, repeatable and has no observable hysteresis [1] (Fig. 2). The measurements from these "Smart Braids" can be used as feedback for the motion control of soft continuum manipulators [4]. Two Smart Braid McKibben muscles were used to control the bend angle of a one-degree-of-freedom planar continuum manipulator (Fig. 3). Using the inductance measurements of the two Smart Braids as feedback, the angle of tip angle of the manipulator was controlled with an average steady-state error of 1.25 ° (Fig. 4).

To measure the inductance, we rely on "Inductance-to-Digital" converters from Texas Instruments [7]. These chips can measure the inductance of up to four circuits in quick succession. This has enabled us to provide inductance feedback for the motion control of complex, multi-degree-of-freedom systems [5].

From a materials robotics perspective, the integration of these conductive circuits into soft actuators and structures could be challenging. The conductors may need to undergo repeated stress and flexure. It can be difficult to select materials and treatments to create proper adhesion between insulated metal wires and a soft substrate. It can also be difficult to integrate fiber placement into a soft fabrication processes. Some have proposed the use of a "sew-and-transfer" method for creating "zig-zag" wire patterns [6]. An alternative is to place the circuits on top of the elastomer and/or fiber-reinforcement structures (e.g. Fig. 3).

A limitation of inductance-based sensing is the tendency of highly conductive or ferromagnetic materials in the immediate proximity of the sensor to bias the inductance value. For sensors that undergo a large relative inductance change, the effect of this bias can be small [1]. For example, placing a steel rod next to a braid for a 29 cm actuator resulted in biases of less than 1.4 mm. However, for circuits that undergo a smaller relative change in inductance, the effect of this bias can be more pronounced [3].

For soft robotics to reach its full potential, it must include systems that can sense and control their own motion. I am looking forward to the opportunity to discuss the opportunities and challenges of this sensing method with the participants in the Material Robotics workshop. I will bring a couple deformable circuits for the workshop attendees to play with. This will likely include a bending bellows and a "Smart Braid." Workshop attendees will be able to deform the circuits and observe the real-time inductance measurements on a screen.

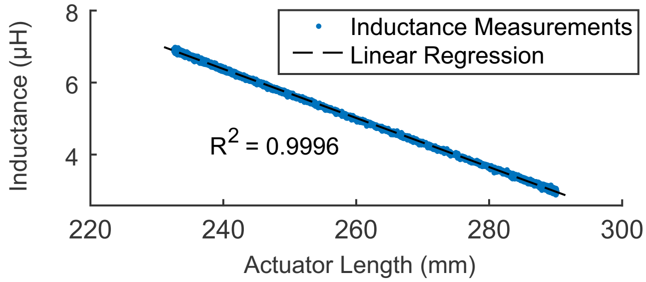

Fig. 2. A contracting fiber-reinforced actuator can be outfitted with a "Smart Braid" that measures the contraction via a linear inductance response. The braid is made from off-the-shelf wires that provide both reinforcement and sensing to the actuator. Sensors such as these can be used to control soft robotic systems driven by fiber-reinforced actuators [4]. Adapted from [1].

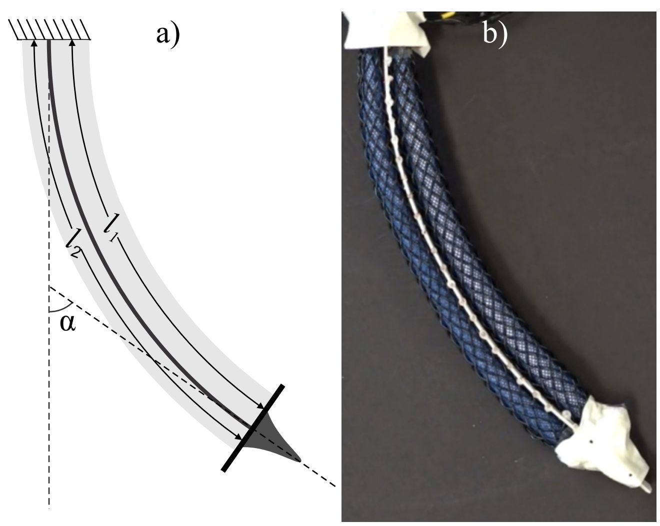

Fig. 3. By attaching two McKibben muscles to a flexible "spine," a planar one-degree-of-freedom continuum manipulator is made. The conductive wires (black) form "Smart Braid" circuits with inductance values that increases as their corresponding actuator contracts. Adapted from [4].

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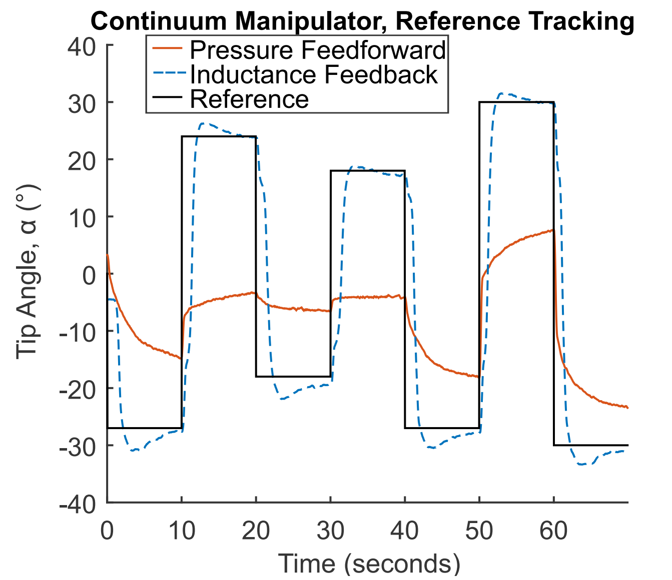

Fig. 4. Using the inductance as feedback to control the tip angle of the Smart Braid McKibben musucle continuum manipulator results in an average steady-state error of 1.25 ° (blue line, partial test shown). This is a dramatic improvement over the performance of an open-loop controller that relies only on the pressure (red line). Adapted from [4].

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