RISE WINTER 2015 – UNDERSTANDING AND TESTING SELF SENSING MCKIBBEN ARTIFICIAL MUSCLES

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Abstract – **Due to their compliant properties, McKibben artificial muscles are well suited for applications in wearable devices and soft robotics since they do not require conventional joints to be affixed to. To make these actuators useful in closed- loop controlled system, a number of challenges must be overcome with respect to measuring the contraction of the muscles. Researchers at the Robotics and Motion Laboratory (RAMlab) at the University of Michigan have developed a way to measure soft actuator motion, by making the braid of the McKibben artificial muscles out of conductive wire. Turning the muscles into an electric circuit allows the measurement of contraction of the actuator through measurements of inductance of the wire braid itself. In my RISE project, I conducted a systematic investigation of these self-sensing McKibben muscles by experimentally characterizing changes of inductance as the muscle contracts. Additionally, I developed a test fixture that enables antagonized testing of pairs of actuators. The fixture will allow variable inertial loads and different lengths of the McKibben artificial muscles to be tested and provides a platform to test control algorithms.**

I. INTRODUCTION

Soft robotics is a relatively new field, with research and development stretching back as far as a decade ago that is heavily influenced by biological systems [1]. These soft robots are the opposite of traditional, rigid robots: their working principle revolves around distributed deformation throughout the robot body to allow conformation to obstacles [1]. They become great alternatives to applications that require human-robot interaction or activity in limited spaces [1].

Due to their compliant properties, McKibben artificial muscles become well suited for applications in soft robotics since they do not require conventional joints. McKibben artificial muscles are the most common type of soft actuators used in robotics. They are pneumatic actuators that expand laterally and contracts longitudinally when filled with pressurized air [2]. McKibben artificial muscles are well suited for applications in wearable devices and soft robotics since they do not require conventional joints to be affixed to.

However, the absence of rigid joints becomes a challenge when it comes to feedback control. Position control remains an obstacle since traditional sensors rely on a fixed datum point to measure accurately, which soft robotics do not provide. To solve this, researchers from the Robotics and Motions Laboratory (RAMlab) from the University of Michigan have found a way to characterize inductance to the contraction of the McKibben artificial muscle [2]. Wyatt Felt from the RAMlab has designed a McKibben artificial muscle prototype that is braided with wire to form a circuit with an inductance that corresponds to different braid lengths [2]. His work also includes prediction of force through measurement of resistance in the wire, though these predictions are less accurate [2].

In this paper, I present my work with the RAMlab on testing the capabilities of this novel sensing system. My work was comprised of two primary projects. First, I characterized the changes in resistance and inductance of the sensor. The resistance experiments I conducted used fixed loads on individual strands of wire. In the inductance tests, I measured the inductance of the sensor braid by itself to characterize the inductance change to the change of braid length. The second part of my work involved designing and building a test fixture as a platform to test the self-sensing braid on McKibben artificial muscles in an antagonized setting for implementation of feedback control.

II. CHARACTERIZING RESISTANCE AND INDUCTANCE TO FORCE OUTPUT AND MUSCLE CONTRACTION

A. Braid Construction

McKibben artificial muscles expand laterally and contracts longitudinally when pressurized. The braid forces the muscle to contract as it expands.

The self-sensing braid was created by weaving wires over a 3D-printed template. The template was designed to affix to a dowel during the braiding process. When the braid is complete, the dowel can be removed and the template can be collapsed and removed from within the braid. When the braid is being woven, the winding angle (the angle with respect to the long axis) is 45 degrees. Once the braid is removed, the template is designed for the braid to be 30 mm long with a winding angle of 20 degrees when surrounding the inner silicone tube (outer diameter of 9.5 mm). A single strand to wire was woven to form the entire braid.

B. Theory

Resistance: In the earlier work developing these sensors [2], the resistance change in the 32 AWG wire (with silicone insulation) relative to the force output of the muscle was nonlinear. For my experiments, I used a braid with a different type of conductor (22 AWG, PVC insulation, DABURN #2671). The goal was to see whether a different type of conductor would exhibit the same nonlinear behavior as seen in [2], and also to determine whether the resistance measurements from the wire would be suitable for force prediction. The force of the load would cause strain in the fibers, which would increase the resistance of the wire. The relationship between resistance and cross sectional area is given by Pouillet's law:

$$R = \rho \frac{l}{A} \qquad (1)$$

where R is the resistance of the conductor, ρ is the electrical resistivity, l is the length of the conductor, and A is the cross sectional area of the conductor.

Inductance: As the braid contracts in length and increase in cross sectional area, the fibers start to align to each other, which causes an increase in inductance, similar to a solenoid. The test results of the inductance-contraction measurement experiment were used to validate two mathematical models that compute inductance: the long solenoid approximation, and the Neumann formula for self-inductance [3].

We chose the long solenoid approximation as one of the verification models because it provided an intuitive understanding to the relationship of the inductance to the braid length and cross sectional area. The assumptions for the long solenoid approximation are that the loops of the coil are horizontal to its long axis (tight winding angles), that the braid is cylindrical, and that its length is much greater than its diameter. For the long solenoid approximation, the inductance L is proportional to the cross sectional area A and inversely proportional to the braid length l:

$$L = \mu_0 \frac{N^2 A}{l} \tag{2}$$

where μ_o is the magnetic permeability of classic vacuum, N is the number of turns of coils.

From Eq. (2), we estimated that inductance decreases when the muscle relaxes, while the inductance increases when the muscle contracts.

The Neumann formula for self-inductance was selected as another model to predict inductance measurements. It breaks down the coil into a number of elements. Its assumptions are that the coil that is being calculated is made up of an infinitesimally thin wire.

$$L = \left(\frac{\mu_0}{4\pi} \oint_C \oint_{C'} \frac{dx\, dx'}{|x - x'|}\right)_{|x-x'|>2a} + \frac{\mu_0}{4\pi} |C| Y + O(\mu_0 a) \tag{3}$$

μ_o is the magnetic permeability of classic vacuum, x and x' are elements along the coil (defined by the curve C, with length $|C|$, Y is the constant that depends on the distribution of the current in the wire (where $Y = 0$ when skin effect occurs, and $Y = ½$ when current is uniform across the wire), a is the radius of the wire, and $|x - x'|$ is the distance between the two differential elements. The second term $\mu_o/4\pi\ |C|Y$ is the correction factor for the inductance, while the third term $O(\mu_o a)$ is the error of the formula.

C. Resistance and Inductance Measurement Methods

Resistance: To measure the resistance in the conductor relative to force output, a length of wire was exposed to various fixed loads. The conductor was looped through a liquid container and over a high metal bar. The ends of the conductor were connected to an NI Digital Multimeter (NI PXI 4072) with a 4 wire resistance measurement (Fig 1). The conductor was subjected to loads from 0 N to 35 N, with varying volumes of liquid water.

Inductance: To measure the inductance of the self-sensing braid relative to its cross sectional area and braid length, I fitted the braid over 7 dowels of different diameters (Fig 1). The leads of the braid were connected to an NI Digital Multimeter (NI PXI 4072) to record inductance. The varying diameters of the dowels provide different cross sectional areas. The braid was stretched tightly over these dowels to constrain the length as well.

D. Results and Discussion

Resistance: The resistance data obtained from varying fixed load on the conductor was inconclusive. The change of resistance in the conductor was too low, and no significant change throughout fixed loads of 0 N to 35 N was able to be recorded over the noise. This rules out the use of resistance to measure force with this thickness of wire.

Inductance: The inductance measured across different dowel diameters was as predicted; the inductance increases as the braid length decreases and as the cross sectional area increases.

The test results were compared to the two mathematical models, and showed high degrees of similarity (Fig. 2).

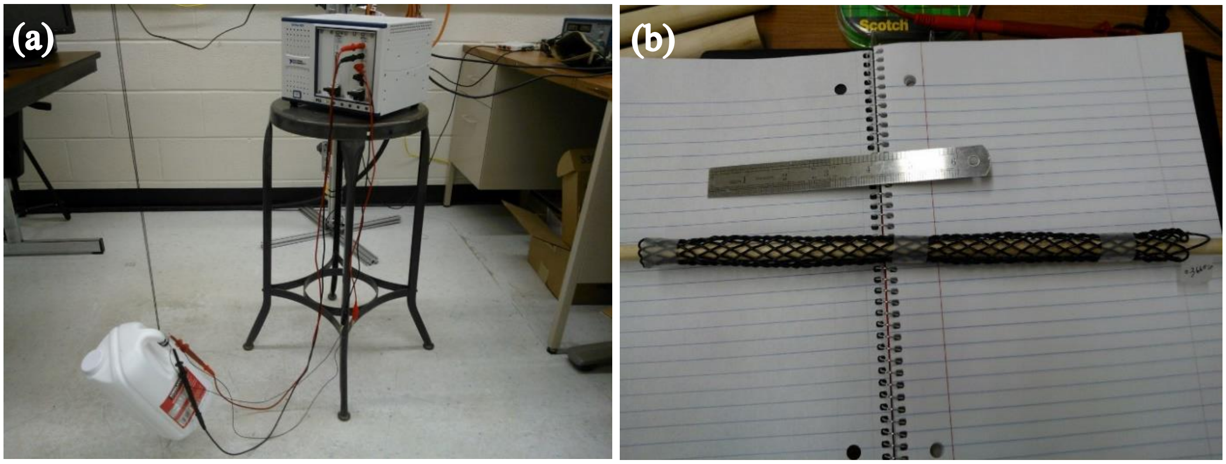

Figure 1. Shown is the resistance measurement set up in (a) and the inductance measurement set up in (b). In (a), for every load increased, the resistance was recorded for three times: the wire was loaded and unloaded for the three trials in order to account for any yielding in the wire. In (b), the braid was taped to the dowel to ensure the cross sectional area (of the braid) along the dowel remains mostly the same.

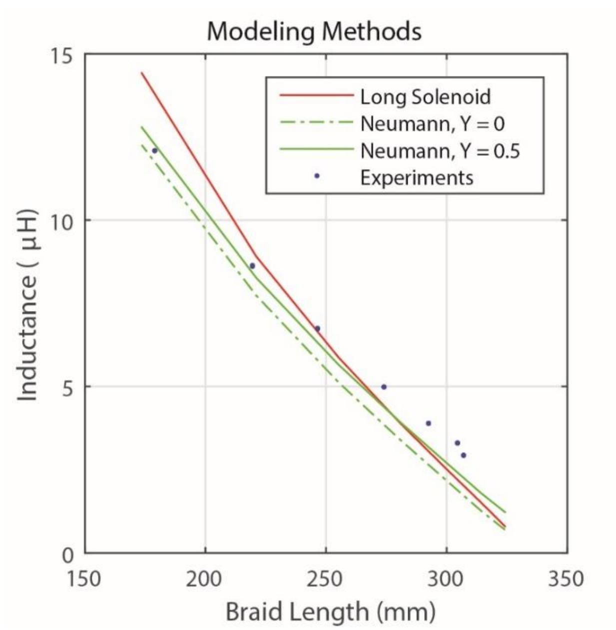

Figure 2. The Neumann formula, used 160,000 elements with two different Y values to provide a range of values to account for different possible distribution of current in the wire. The experimental data (dots) are very similar to both mathematical models.

III. BUILDING TEST FIXTURE

A. Introduction

McKibben Artificial Muscle: Each braid was fitted to silicone tubes with outer diameter of 9.5 mm to form an actuator. The ends of each tube were then fitted with nylon barbed tube straight connectors (McMaster, 5463K578), with a toothed washer (McMaster, 90069A130) glued to allow the braid ends to hook onto it. The hooked ends were also filled with hot glue to ensure firm attachment of the braid to the muscle. The leads of each muscle braid were soldered to the TI-LDC1000-EVM Inductance-to-Digital Converter that allows rapid measurement of inductance. The braids were connected in parallel with 390 pF capacitors to form resonant circuits.

Test Fixture: We proceeded to design and build a test fixture that allows antagonized testing of the McKibben artificial muscles. The test fixture built allows antagonized testing of the muscles and is able to provide angle measurements via a potentiometer (Mouser Electronics, 882-MW22B-3-10K) attached to a shaft that connects the two muscles (Fig. 3). The test fixture also contains a lever arm that allows controlled force disturbance to the system or addition of inertial loads.

The test fixture has two platform levels. The top level houses the muscles, the pulley and the lever arm, while the lower platform houses the pressurized air system. The muscles receive pressurized air from the same source, but have separate valves that control flow rate into them.

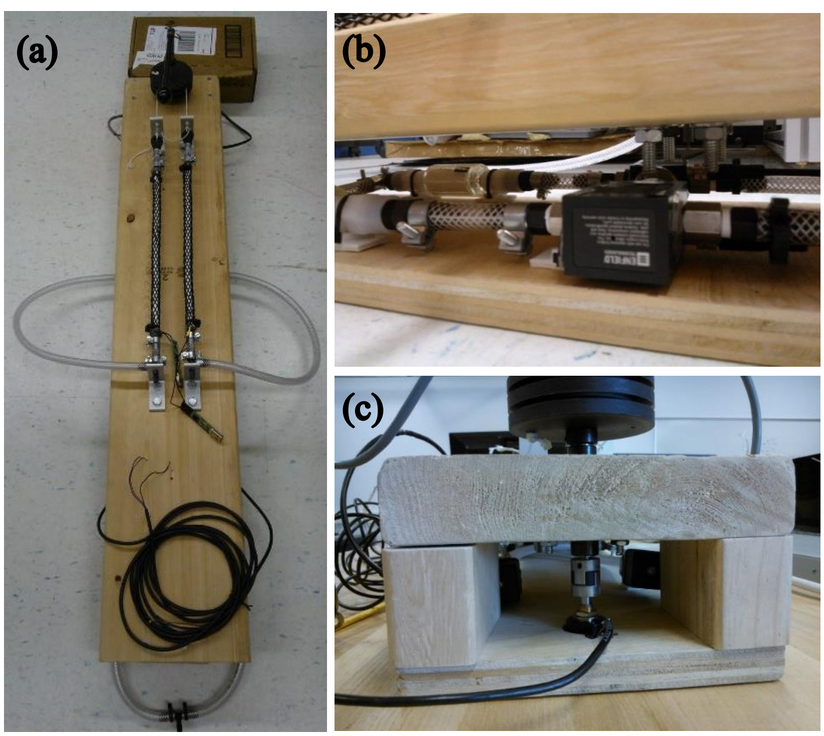

Figure 3. The McKibben artificial muscles are positioned side by side on the top platform in (a), and receive pressurized air through the tubes on the bottom platform. In (b) the valves control the flow of pressurized air into the muscles. In (c) the shaft is connected to the potentiometer via a flexible shaft coupler (McMaster, 6408K9 & 6408K61) that accounts for minor misalignments.

B. Theory

The inductance measurements are taken with a TI-LDC1000-EVM Inductance-to-Digital Converter, which is connected to a resonant circuit made up of the smart braid and a small capacitor in parallel. By using a frequency counter, the TI-LDC1000-EVM measures the circuit's frequency of oscillation, f_{sensor}. The sensor frequency is then used to determine the inductance of the smart braid, *L*, using the value of the capacitance, *C*:

$$L = \frac{1}{C \times (2\pi \times f_{sensor})^2} \tag{4}$$

IV. FUTURE WORK

The completion of the test fixture will allow experimentation to test the feasibility of the novel inductance sensors for feedback control. We plan to develop closed loop controllers that receive feedback through either the potentiometer signal or the inductance signal (Fig. 4). The controller that senses with the potentiometer will be set as a benchmark to compare the controller that uses the novel sensing method.

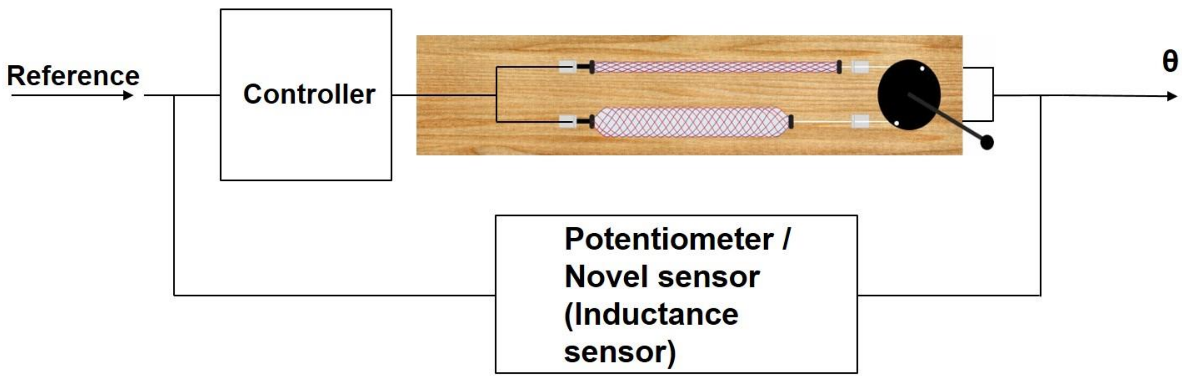

Figure 4. The controller will be controlling the pressurized air flow input to the system, and will receive feedback via either the potentiometer or the inductance measurement.

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