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Self-Sensing Electro-Ribbon Actuators

Simon Bluett, Tim Helps, Majid Taghavi, and Jonathan Rossiter

***Abstract*—In this letter, we investigate the viability of capacitance self-sensing of electro-ribbon actuators, allowing them to be used simultaneously as an actuator and a sensor. Initially the electro-ribbon actuator was implemented only as a sensor, and it was found that the exponential relationship between capacitance and displacement made the device a poor sensor at distances greater than 2 mm. When used simultaneously as an actuator and a sensor, the 'zipping' motion of the electrodes changed this relationship, making it more suitable for position sensing. Capacitance was found to be a good indicator of the amount of zipping experienced by the electrodes. For effective displacement sensing, the mass of the the load being applied to the actuator should be known. Finally, a closed-loop PI position control system using self-sensing feedback was implemented. The results demonstrated that, provided the applied load is known, capacitive self-sensing can be used to control the position of electro-ribbon actuators with reasonable accuracy.**

***Index Terms*—Soft sensors and actuators, modeling, control, and learning for soft robots, compliant joint/mechanism.**

I. Introduction

Traditionally, robots are manufactured using rigid materials and are designed to work in structured environments, performing repetitive tasks with high precision. In recent years, there has been a shift to develop more dynamic systems using soft and compliant materials which can adapt to their surroundings. Electrostatic actuators have gained popularity due to their small form factor, silent operation, readily-available power source, and potential for large forces [1], [2]. Electrostatic actuators fundamentally consist of two electrodes, separated by an insulator. As a voltage is applied across the electrodes, an attractive electrostatic force—known as Maxwell stress—is generated, pulling the electrodes together and providing a mechanical output.

Since the force is greater at smaller distances, due to inverse square proportionality, electrostatic actuators are widely used in micro-electromechanical systems (MEMS) [3], [4]. One method of increasing the stroke length is to allow the device to actuate in a "zipping" manner [5]. By clamping the electrodes together at one/both ends, the distance between the electrodes is much smaller at the clamps than at the point where the load is attached. Consequently, a force gradient is generated when a voltage is applied, causing the electrodes to progressively move together in a zipping motion [6].

The closing force exerted by electrostatic actuators can be increased by raising the voltage applied across the electrodes; for example, dielectric elastomer actuators (DEAs) are often operated at voltages exceeding 2 kV [1]. However, the maximum voltage is limited by the phenomenon of dielectric breakdown, which occurs when the applied electric field exceeds the breakdown strength of the dielectric material. For DEAs this can cause permanent damage, preventing any further operation [7]. Recently, it was shown that submerging and encapsulating the actuator within a dielectric fluid could increase the performance of electrostatic devices [3], [8]. Due to the higher permittivity of oil compared to air (2.75 times higher for olive oil [3]), the fluid amplifies the achievable closing force, while the raised breakdown strength of the oil allows higher electric fields to be sustained. Moreover, liquid dielectrics have been shown to display self-healing properties in the aftermath of dielectric breakdown events [9].

The electro-ribbon actuator is a new type of soft actuator that contracts using the Dielectrophoretic Liquid Zipping (DLZ) actuation concept [10] (Fig. 1). By adding a small drop of liquid dielectric to the zipping points (the points at which both insulated electrodes are closest), these actuators achieve almost 92% of the closing force compared to full encapsulation in dielectric fluid [10]. Due to dielectrophoresis, the high-permittivity dielectric fluid is attracted to the zipping points of the electrodes where there is a higher electric field density [11]. This ensures that the fluid is retained in the region where it increases closing force the most, such that only a small quantity of oil is required. This implies lower actuator mass when compared with fully-encapsulated hydraulically amplified self-healing electrostatic actuators (HASEL) [9], [12], while still benefiting from the amplification of a liquid dielectric. Electro-ribbon actuators achieve high contractions up to 99.8% [10], comparing favourably with the contractions of DEAs (46% [13]). Due to the thin and lightweight nature of the electro-ribbon actuator, it potentially could be used in compact folding structures such as solar panels and solar sails on spacecraft where traditional actuators are too bulky. Other potential applications include solenoids, robotic grippers, and locomotion robots [10].

While the inherent compliance of soft materials can help to improve an actuator's reliability, versatility and shock-absorbing

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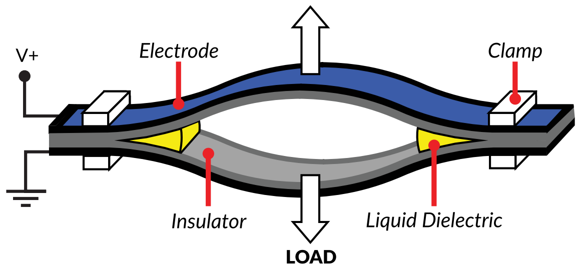


Fig. 1. Diagram of the electro-ribbon actuator.

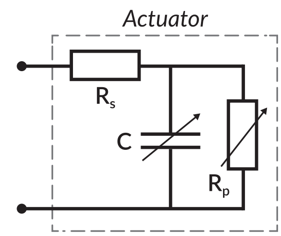
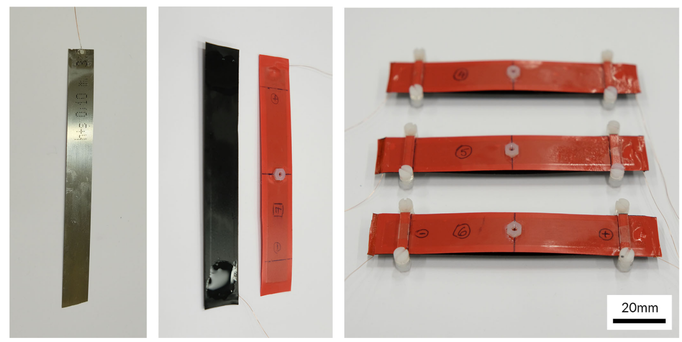


Fig. 2. Equivalent circuit model of the electro-ribbon actuator.



(a) (b) (c)

Fig. 3. Images showing the fabrication steps of the actuator. (a) Shows a steel electrode with a wire soldered to one end, while (b) shows PVC insulation tape applied to each electrode. (c) Displays 3 identically fabricated actuators, whose electrodes are clamped together with acrylic brackets.

characteristics when interacting with the environment [14], it also makes them difficult to control precisely. Often, additional external sensors are required to monitor and compensate for the deformation of soft systems during operation. However, in a process known as *self-sensing*, it is possible to simultaneously use some actuators as sensors by monitoring one of the characteristics of the device which varies as it undergoes deformation. For electrostatic actuators, electrical capacitance is commonly used to estimate deformation during operation; this process has been demonstrated on DEAs [15]–[17] and HASEL actuators [9], [12].

In this letter, we investigate the application of capacitance self-sensing to electro-ribbon actuators. The relationship between the capacitance and deformation of electro-ribbon actuators is analysed when used exclusively as a sensor. This relationship is re-examined whilst performing simultaneous actuation and sensing. Finally, the results are used to develop a closed-loop position control system using self-sensing feedback; the aim of this demonstration is to identify the factors affecting the implementation of self-sensing in practice.

II. System Design

A. Self-Sensing of Actuator Capacitance

The capacitance of electrostatic actuators can be described using a parallel plate capacitor model [18]:

$$C = \frac{\epsilon_r \epsilon_0 \, A}{T} \tag{1}$$

where ϵ_0 and ϵ_r are the permittivity of free space and the relative permittivity of the dielectric respectively, A is the area of the electrodes and T the thickness of the dielectric. For the electro-ribbon actuator, the main contributor to capacitance is the zipped area where the electrodes are in close proximity to one another (at the zipping points, where T is small). As the actuator contracts, the zipped area increases, causing an associated increase in capacitance. However, the actuator is also subject to the non-ideal resistance of the electrodes, and a small parasitic current flowing through the dielectric. Similar to DEAs [15]–[17], these factors can be quantified in the equivalent circuit model of the actuator as a series (R_s) and parallel (R_p) resistance respectively (Fig. 2). During operation, the series resistance of the inextensible electrodes remains constant, while the parallel dielectric resistance varies as the actuator extends and contracts.

A self-sensing unit (SSU) [15], [16] was used in this research to provide the actuation voltage to the electro-ribbon actuator, while simultaneously measuring capacitance. The capacitance of the actuator is measured by superimposing a low-amplitude, but high-frequency *sensing signal* onto the high-voltage *actuation signal*. The SSU monitors the voltage and current being supplied to the actuator, and detects changes in this time-varying signal as the device operates. By applying an algorithm based on multidimensional linear regression, the SSU calculates the values for the capacitance and the series and parallel resistances of the actuator in real time [15]. The SSU was connected via USB to a computer, where a LabVIEW program was employed to monitor the capacitance and control the actuation voltage. The capacitance was estimated with a precision of ± 1 pF and a refresh rate of 25 Hz.

B. Fabrication

A diagram of the electro-ribbon actuator is shown in Fig. 1, while Fig. 3 shows the main fabrication steps. The electrodes of the actuator were fabricated using high-grade steel (1.1274 carbon steel, H+S Präzisionsfolien GmbH, Germany) of thickness 0.2 mm and width 12.7 mm. The electrodes were cut to a length of 100 mm, after which a thin copper wire was soldered to one end of each electrode. Both sides of each electrode were covered in one layer of PVC electrical insulation tape (AT7, Advance Tapes, UK), before being clamped together using laser cut acrylic brackets. The clamps were positioned 10 mm from each end of the electrodes. Finally, M3 nylon nuts

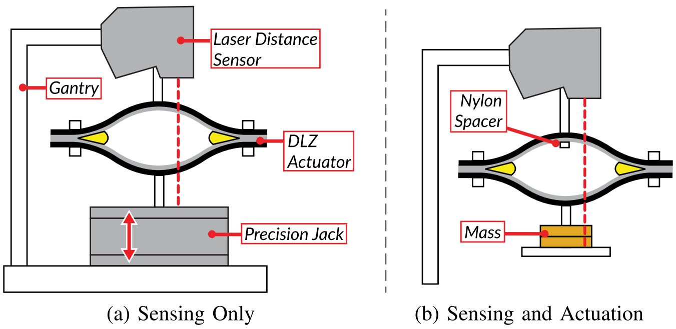


Fig. 4. Diagrams of the experiment apparatus. Configuration (a) was used to precisely control the displacement of the actuator, while (b) allowed the electro-ribbon actuator to move freely under a load. For safety, the apparatus was contained within a high-voltage enclosure.

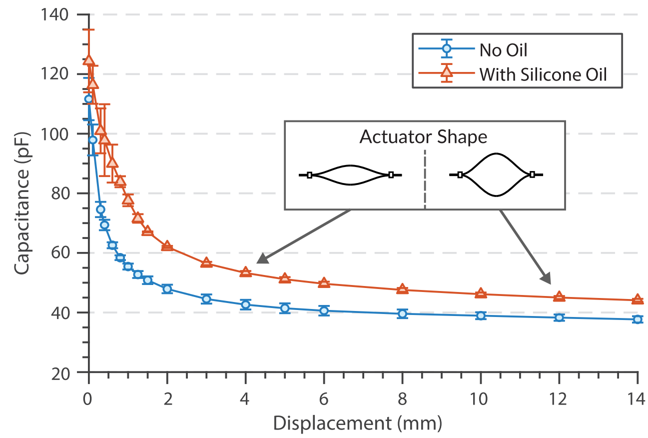


Fig. 5. Electrical capacitance with respect to vertical displacement ($\pm$0.005 mm) of the electro-ribbon actuator when used exclusively as a sensor. Results are averaged over 3 trials using identically manufactured actuators. The approximate shape of the actuator as it deforms is also illustrated (proportions not to scale).

were attached using cyanoacrylate glue to the outside-middle of both electrodes, providing locations where the actuator could be connected to the gantry and the load. For all experiments, silicone oil of viscosity 50 cSt (# 378356, Sigma-Aldrich, USA) was used as the dielectric fluid.

III. Experiment Design

A. Sensing Only

Initially, the electro-ribbon actuator was implemented exclusively as a sensor, allowing the electrical characteristics to be analysed without the presence of a high voltage actuation signal. Fig. 4(a) shows the experiment setup and apparatus. A mechanical jack controlled the displacement at the centre of the actuator and a laser distance sensor (LK-G152, Keyence, Japan) measured this displacement. The capacitance of the electro-ribbon actuator was recorded at discrete displacement intervals using a precision LCR meter (E4980, Keysight, USA). The actuator was first tested without any dielectric fluid, after which the tests were repeated adding 0.5 ml of silicone oil to each zipping point. To measure the repeatability of the readings, the experiment was repeated on 3 separate but identically manufactured actuators.

B. Simultaneous Actuation and Sensing

The ability of electro-ribbon actuators to be concurrently employed as a sensor and an actuator was tested by allowing the device to actuate freely under a variety of different loads. As illustrated in Fig. 4(b), a fixed load was attached to the bottom electrode of the device to provide a downward force, extending the actuator when no voltage was applied. The SSU was used to actuate and sense the capacitance of the actuator. Displacement during actuation was measured with a laser distance sensor, while the amount of ‘zipping’ experienced by the electrodes was recorded using a camera (motion tracking in Adobe After Effects). 1.5 ml of silicone oil was added to each zipping point of the electrodes; this was an increase compared to the sensing-only experiment, since it was found that dielectric breakdown occurred above 4 kV when a lower quantity of oil was used. A 2 mm nylon spacer was glued to the inside-middle of the top electrode, to prevent the adhesive and cohesive forces of the oil from causing the electrodes to adhere together when the actuator fully contracted. The test consisted of applying a slow sinusoidal actuation signal (0.02 Hz, 0 to 5 kV) to the electro-ribbon actuator, causing it to contract and extend. The test was repeated 3 times on three identically manufactured actuators (9 tests total).

C. Closed-Loop Position Control

The same apparatus was used as in Fig. 4(b). A load of 30 g was attached to the bottom electrode, and this mass was kept constant throughout the position control experiments. A proportional-and-integral (PI) controller was implemented in LabVIEW, which controlled the actuation voltage being supplied to the electro-ribbon actuator. This program obtained the real-time capacitance reading from the SSU, converted it into a displacement estimate (using relationships established in the simultaneous actuation and sensing experiment), and used this as feedback for the PI controller. The gain parameters of the controller were tuned by using trial and error to obtain an initial stable gain combination, after which the step response of 60 neighbouring gain combinations were systematically tested. A gain combination that provided a compromise between low rise time, settling time and percentage overshoot was chosen. Finally, the performance of the tuned controller was tested with a variety of step and sinusoidal position sequences.

IV. Results and Discussion

A. Sensing Only

Fig. 5 shows the capacitance of the electro-ribbon actuator when used as a sensor for displacements between 0—14 mm. The capacitance was seen to exponentially decay as the actuator extended from its fully contracted state, becoming asymptotic as the displacement exceeded 2 mm. The reason for this exponential relationship is that when electro-ribbon actuators are used as sensors, the majority of the change in zipped area occurs immediately (as displacement increases from 0 to 2 mm). Beyond this point, the zipped area only changes slightly as displacement is increased further (Fig. 5, inset). Since the zipped area is the main contributor to capacitance, the majority of capacitance change also occurs at low displacements. Due to the positioning of the acrylic clamps, 10 mm of the electrodes were held together in a zipped state at each end of the actuator throughout deformation, resulting in the asymptotic capacitance at high displacements.

Similar behaviour was observed when 0.5 ml of silicone oil was added to each zipping point of the actuator, but the asymptotic capacitance (at 14 mm extension) was raised by approximately 7.5 pF compared to the dry test. This overall increase in capacitance was caused by the higher permittivity of the small droplets of silicone oil retained between the zipping points of the electrodes, which was 2.71 times higher than that of air. The results showed that when the electro-ribbon actuator was used only as a sensor, capacitance was not an ideal metric with which to estimate displacement. Although the device displayed reasonable sensitivity (using capacitance to predict displacement) for distances between 0-2 mm (140 to 25 pF/mm, no oil), the sensitivity rapidly declined (below 1 pF/mm, no oil) as the electrodes were extended further. Consequently, using electro-ribbon actuators for sensing would only be suitable for measurements of small displacements.

Furthermore, it was noted that when dielectric fluid was added, there were no dielectrophoretic forces attracting the silicone oil to the zipping points of the electrodes. Consequently, the oil spread evenly across the surface of the bottom electrode. When the displacement was reduced below 0.5 mm, the oil came into contact with the top electrode and caused a large, sudden change in capacitance. This can be seen in Fig. 5 as an increase in standard deviation. Since the displacement at which this sudden increase occurs is highly dependent on the quantity of oil (which may change over time as some spreads away from the zipping points), this further reduces the accuracy of the liquid-dielectric-enhanced electro-ribbon actuator when used only as a sensor.

B. Simultaneous Actuation and Sensing

When the electro-ribbon was actuated with a high-voltage signal, the manner in which it deformed changed due to the 'zipping' actuation mechanism (Fig. 8, inset). When electro-ribbon actuators are used as sensors, the majority of zipped area change occurs at low displacements. In contrast, because actuated electro-ribbon actuators progressively zip together from each zipping point, the zipped area increases more gradually with respect to displacement (Fig. 6). The non-linearity in the relationship is a result of the stiffness and bending characteristics of the steel electrodes, causing the change in displacement to decrease as the zipped area progressively increases. Capacitance is inversely proportional to the distance between the electrodes Equation (1), therefore the zipped sections of the actuator (where the distance is smallest) are the main contributors to the overall capacitance of the electro-ribbon actuator. This is illustrated in Fig. 7; capacitance is approximately directly proportional to the quantity of zipping. The same relationship persisted for all applied loads.

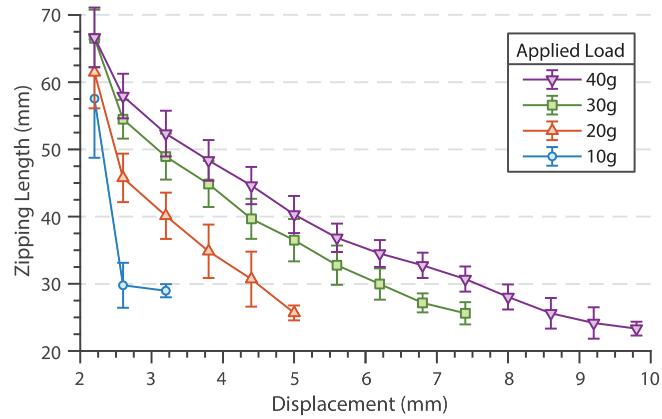


Fig. 6. Average quantity of electrode zipping with respect to the displacement ($\pm$0.1 mm) of the electro-ribbon actuator. (Averaged over 9 tests).

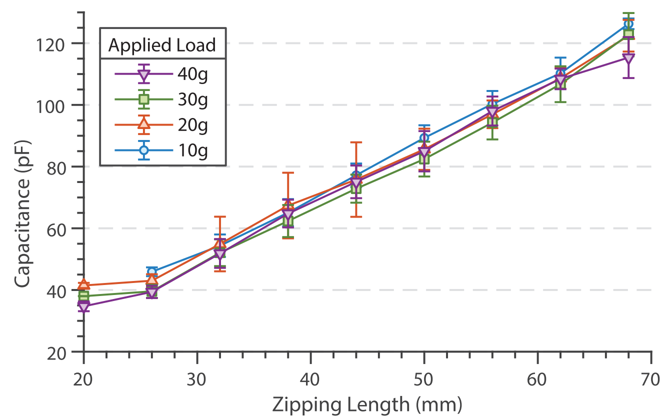


Fig. 7. Capacitance of the electro-ribbon actuator with respect to the amount of zipping ($\pm$1 mm) experienced by the electrodes. (Averaged over 9 tests).

While capacitance was a good indicator of how far the electrodes of the electro-ribbon actuator had zipped together, it was found that the displacement at the centre of the actuator was also dependent on the applied load. Fig. 6 shows that for a specific quantity of zipping, increasing the load had the effect of enlarging the deformation of the open section of the actuator, increasing overall displacement. Consequently, to estimate the motion of the load using capacitance self-sensing, the relationship between the displacement and quantity of zipping first needed to be established. This was only possible when the load applied to the actuator was known. Fig. 8 illustrates the relationship between capacitance and displacement, and confirms that the load needs to be identified to estimate position using self-sensing. The shape of the profile in Fig. 6 is similar to Fig. 8, since the relationship between capacitance and quantity of zipping is almost linear. The non-linearity is caused by the bending characteristics of the electrodes as noted in the zipping-displacement relationship.

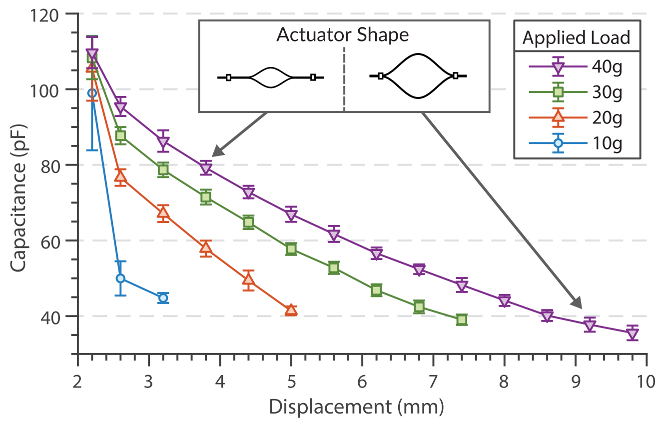


Fig. 8. Electrical capacitance of the electro-ribbon actuator with respect to the displacement (± 0.1 mm) of the load, averaged over 9 tests. The deformation of the actuator as it undergoes zipping is illustrated (proportions not to scale).

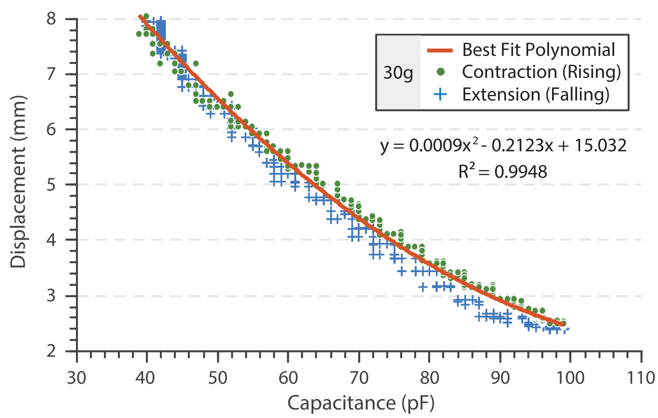


Fig. 9. Relationship between displacement and capacitance for a load of 30 g, with the hysteresis between the extension and contraction states shown. The combined best fit quadratic polynomial and corresponding correlation coefficient are also shown. This equation was used in the subsequent closed-loop position control experiments.

In Fig. 8, changing the mass of the applied load changed the displacement range of the actuator, while the capacitance range remained relatively constant. Consequently, the sensitivity of capacitive self-sensing reduces as the applied load is increased.

In Fig. 9, it is shown that for a load of 30 g, the dependence between capacitance and displacement can be well-approximated with a quadratic polynomial. When compared to the sensor-only configuration of the electro-ribbon actuator, this relationship has a much more consistent sensitivity across the entire operating range of the actuator. For a load of 30 g, the sensitivity ranged from 8 to 16 pF/mm. The accuracy of the quadratic expression was limited by the repeatability and precision of the capacitance-displacement relationship; the maximum recorded error was 12.57% and the standard deviation from the ground-truth was 0.289 mm. Fig. 9 also shows the hysteresis between the extension and contraction of the actuator. This was caused by the cohesive forces of the dielectric fluid, which resisted the separation of the electrodes and affected the relationship between zipping and displacement. This effect could potentially be reduced by using oil of lower viscosity or surface modifications of the insulator.

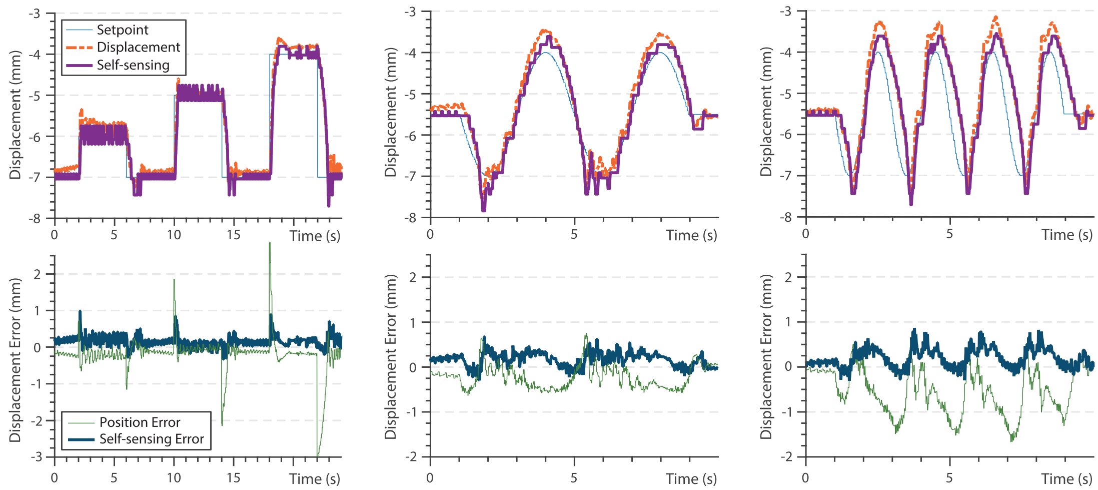
C. Closed-Loop Position Control

Tuning of the PI gain parameters was conducted through a combination of trial and error and systematic testing; optimum parameters of ($K_p = 2000$) and ($K_i = 2 \times 10^5$) were chosen. Fig. 10 shows the response of the tuned PI controller to a variety of position sequences. The step sequence demonstrates the system's ability to maintain specific displacements, while the sinusoidal sequences illustrate how it can track a continuously changing target. Overall, the system was able to track the position sequences with reasonable accuracy at frequencies below 0.5 Hz; the self-sensing position estimate remained within ± 1.07 mm of the displacement recorded by the laser distance sensor for all sequences tested.

However, the test highlighted several issues affecting the performance of the closed-loop controlled actuator. The limited precision (± 1 pF) and low refresh rate (25 Hz) of the SSU introduced noise into the controller, causing the actuator to oscillate about the target position. This was most visible in the step sequence in Fig. 10(a), when the system was trying to maintain a constant position. The low sampling rate may also have contributed to a rise in the maximum error of the self-sensing estimate at higher frequencies, from ± 0.488 mm at 0.125 Hz to ± 1.054 mm at 1.0 Hz.

The position control performance for the sinusoidal sequences deteriorated when the actuation frequency was raised above 0.5 Hz. The maximum position error was seen to rise from ± 1.674 mm at 0.5 Hz to ± 3.113 mm at 1 Hz. This limitation was also noted in previous research [10]; the maximum frequency at which the electro-ribbon actuator can cycle between open and closed is limited by the speed at which the inertial load can restore the actuator to its extended state. While the contraction force can be increased by applying a higher voltage, the extension of the actuator is defined by the force of gravity acting on the load and the adhesive and cohesive forces between the dielectric liquid and the insulator, which resist the ribbons' separation. Since the time taken to fully extend the actuator is proportional to the stroke length of the device, higher speed operation can be achieved by reducing the maximum stroke length (displacement) of the actuator [10] and using oil of lower viscosity [12]. Alternatively, a spring or elastic band could be used rather than an inertial load to provide a larger restoring force [12].

The difference between the extending and contracting mechanisms was seen to affect all of the tested position sequences. The rise time was consistently faster than the fall time in the step sequences, while the position error was higher in the sinusoidal sequences when the signal was falling (actuator extending) rather than rising (contracting). Other factors which may have contributed to this difference were the voltage bifurcation caused by the pull-in instability of the electro-ribbon actuator—a phenomenon which has extensively been studied for MEMS actuators [4]. Depending on the impedance properties



(a) Step Sequence (b) 0.25Hz Sequence (c) 0.5Hz Sequence

Fig. 10. Response of the PI-controlled self-sensing electro-ribbon actuator to a variety of position sequences. The target position (setpoint), the position recorded by the laser distance sensor (displacement), and the self-sensing position estimate (self-sensing) are shown in the top graph. The lower graph highlights the error between the actual and target positions (position error), and the error between the self-sensing estimate and the actual position (self-sensing error).

of the actuator and impedance and current limit properties of the high-voltage power supply, charging and discharging times may also be a factor.

V. Conclusion

In this letter, we demonstrated that capacitive self-sensing can be applied to electro-ribbon actuators, facilitating closed-loop control without the use of any additional external sensors. The results show that capacitance is a good indicator of the amount of zipping that the electrodes of the actuator have experienced. However, the unique curved shape and the zipping actuation mechanism of the electrodes implies that precise position estimation can only be performed when the load applied to the actuator is known. When the load remained constant, the capacitance and displacement of the electro-ribbon actuator followed a quadratic relationship. In the future, we intend to improve the self-sensing apparatus and algorithm to operate at higher sampling frequencies, allowing the dynamic performance of the electro-ribbon actuator to be studied in further detail. We also plan to investigate whether the applied load may be predicted using the relationship between applied voltage and capacitance. Finally, we plan to apply self-sensing to a variety of electro-ribbon actuators with different shapes and architectures, and to quantify the impact of externally applied deformation to the self-sensing robustness and accuracy of the actuator.

Data Access Statement

Data necessary to support conclusions are included within this letter.

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