Experimental Characterization and Modeling of the Self-Sensing Property in Compliant Twisted String Actuators

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Abstract—Twisted string actuators (TSAs) have exhibited great promise in robotic applications by generating high translational force with low input torque. Despite great success, it remains a challenge to reliably estimate the strain of TSAs using compact solutions while maintaining actuator compliance. The inclusion of position sensors not only increases system complexity but also decreases system compliance, a property often crucial in soft robots. We recently constructed a compliant TSA with self-sensing capability by adopting conductive and stretchable super-coiled polymer (SCP) strings; however, only quasi-static measurements of the strain-resistance correlation were obtained. This study proposes a strategy to experimentally characterize and model the transient self-sensing property in compliant TSAs. The correlation between resistance and strain is characterized under different motor twisting sequences and step durations, and exhibited transient decay, hysteresis, and creep. A self-sensing model that consists of a log-based nonlinear term, a rate-dependent Prandtl-Ishlinskii hysteresis term, and a creep term is proposed for the compliant TSAs. Experimental results confirm the high effectiveness of the proposed self-sensing approach, with the average model validation error less than 0.036 cm.

Index Terms—soft sensors and actuators, soft robot materials and design, actuation and joint mechanisms

I. INTRODUCTION

TRADITIONAL electromagnetic motors and hydraulic actuators are precise and strong, but rigid, heavy, and can be potentially dangerous. In contrast, artificial muscles exhibit desirable traits of compliance, high power-to-weight ratio, low mass \cite{1}-\cite{3}, and have strong potential as driving mechanisms for many emerging robotic applications \cite{4}-\cite{6}.

The twisted string actuator (TSA) is an artificial muscle technology that consists of one or more strings connected to an electric motor on one end and a load on the other end \cite{2}. As shown in Fig. 1(a), the actuation is realized through the twisting of the strings by the motor, which results in contraction, thereby displacing the load in a linear direction. TSAs are advantageous over a winch connected to a motor because TSAs can output greater forces with lower input torques. TSAs exhibit high energy-efficiency and can exert more stress than skeletal muscles \cite{2}. Ultra-high-molecular-weight polyethylene is the most commonly used string material. TSAs have been used in various robotic applications, such as robotic gloves and robot exoskeletons \cite{7}.

Despite great success in various aspects of TSAs, it remains a challenge to reliably estimate their strain using compact solutions while maintaining actuator compliance. There are two main approaches to realize strain sensing for TSAs. Firstly, the strain is estimated by relating their strings’ rotations to their change in length \cite{8}-\cite{10}. Although efficient, this approach not only introduces a constraint to require motors with a rotation sensing mechanism that is often not found in small-sized lightweight motors but is also less robust. A small disturbance, like load variation, could result in a large length estimation error. Secondly, external position sensors lead not only to increased system cost, size, and complexity but also decreased actuator and system compliance \cite{11}. This is undesirable for applications like soft robots, healthcare robots, and human-robot interaction where closed-loop control is often required while maintaining system compliance. Therefore, a self-sensing scheme that continuously estimates the strain of TSAs based on an inherent property of the strings themselves is strongly desirable.

In self-sensing, the variable of interest of the actuator (typically a mechanical property) is estimated by another variable relevant to the actuator (often an electrical signal) that is easier to obtain, thus resulting in a compact system. Self-sensing

![Fig. 1. (a) Illustration of the compliant super-coiled polymer (SCP)-based twisted string actuator (TSA) that changes electrical resistance when in operation. (b) Sample plot depicting the transient self-sensing measurement of a compliant TSA in terms of length and resistance values under step twisting sequences.](image-url)
has been realized in soft actuators such as dielectric elastomer actuators \cite{11}, piezoelectric actuators \cite{12}, and shape-memory alloy actuators \cite{13}, where their strain is estimated by their capacitance or magnetic permeability. In self-sensing of the TSA, it is desirable to estimate its strain based on an electrical signal of the actuator. Unlike many other soft actuators, TSAs are unique in that the actuator only consists of two or more strings connected to a motor with no constraints on the type/material of strings. Therefore, replacing the typically adopted strings with novel strings that can self-sense their strain during twisted actuation may enable self-sensing TSAs. As a recent technology, super-coiled polymer (SCP) strings have attracted much attention because they are compliant, lightweight, elastic, and often electrically conductive \cite{3}, \cite{14}, \cite{15}. While existing studies mostly employed SCP strings as actuators \cite{16}–\cite{18}, there is growing interest in adopting SCP strings as sensors. In \cite{19}, a linear relationship between the resistance and the length of SCP strings was observed, and its sensing property was demonstrated in a soft robot. Bending nylon actuators have been controlled using an open-loop strategy \cite{20}. However, open-loop control is not desired in this study’s compliant TSAs because the dynamics of the motor and strings must be known. Self-sensing has also been implemented in Joule-heated SCPs by measuring the electrical impedance of a wire wrapped around the actuator \cite{21}. However, wrapping a wire around a TSA can be challenging – the actuator in \cite{21} was helical with a mandrel diameter of 5 mm, while the SCPs in our study are not mandrel-coiled and resemble cylinders. In our recent work \cite{22}, \cite{23}, design, preliminary testing, and modeling of the self-sensing property of compliant TSAs were presented. Our recent studies indicated that by adopting SCP strings in the TSAs, higher strains compared to traditional TSAs can be obtained by thermally actuating the SCP strings. A demonstration of a soft gripper powered by these compliant TSAs showed strong potential in soft robots \cite{23}.

Although the recent studies on strain self-sensing compliant TSAs \cite{22}, \cite{23} confirmed the strong promise to incorporate SCP strings into TSAs, the practical realization to reliably estimate compliant TSA’s strain using a self-sensing approach posed several notable challenges. Firstly, only the quasi-static resistance was correlated with the strain and captured by a rate-independent Preisach hysteresis term \cite{22}. This is practically undesirable since it was shown that the resistance took as long as two minutes to reach steady-state value. Also, each experiment consisted of only one cycle of twisting and untwisting \cite{22}. The twisting of the SCP strings in compliant TSAs results in unique resistance responses that include an initial spike followed by persistent decay irrespective of the input, as shown in Fig. 1(b). Although similar transient responses have been exhibited by other smart materials, such as silicon-based elastomers \cite{24} and carbon nanotube-based elastomers \cite{25}, \cite{26}, limited studies have been conducted to capture these behaviors. Lastly, besides the unique spike and transient decay responses, the strain-resistance relationship also exhibits hysteresis and creep, further complicating the self-sensing modeling of the compliant TSAs. In our previous work, the transient and creep properties were not studied \cite{22}, \cite{23}.

In this paper, the transient self-sensing behavior between the resistance and the strain of compliant TSAs is experimentally characterized under different motor twisting sequences and step durations. A large number of actuation cycles are captured, including an experiment lasting over two hours to measure the actuator’s self-sensing lifetime. A detailed experimental study depicting the nonlinear strain-resistance correlation of the TSA, which contains transient decay, hysteresis, and creep nonlinearities, is presented. Furthermore, a mathematical model capturing the self-sensing behavior of the compliant TSA is proposed. The average modeling errors are less than 0.035 Ω (0.65% of the overall resistance) and 0.036 cm (0.15% of the overall length) in the strain-resistance model and self-sensing model, respectively. The proposed model, with minor modifications, could apply to other materials that show similar transient responses.

II. EXPERIMENTAL CHARACTERIZATION

A. Fabrication and Setup

1) Assembly of TSAs: In this study, a TSA made from two SCP strings of equal length was used. The strings remained taut by vertically hanging a load at the bottom end of the strings and fixing the motor to the opposite end. The end of the strings attached to the load was constrained such that it did not rotate. Twisting the TSA would shorten its length to generate linear motion. More strings can also be included in the TSA design \cite{2}. The readers are referred to \cite{9} for more information on TSA.

2) Fabrication of SCP Strings: Based on our previous study \cite{16}, the V Technical Textiles Conductive Yarns (110/34 dtex, Denier:110/34f) were used to fabricate the conductive SCP strings. First, a given number of threads (8 threads in this work) were twisted by a motor until they formed coils, after which the structure was double-backed to balance the torque induced during the insertion of the twists. Since the SCP strings were only twisted, heat treatment was not necessary, although it is a standard procedure when SCP strings are thermally-actuated \cite{15}, \cite{16}.

3) Experimental Setup: Similar to our previous studies \cite{22}, \cite{23}, the TSA was mounted vertically with a stepper motor (NEMA 17HS4401 with A4988 driver) at the top, SCP strings in the middle, and the load at the bottom, as shown in Fig. 2. A custom-designed printed circuit board (PCB) measured the electrical resistance. The PCB was mounted near the motor and featured a hole that allowed the SCP strings to maintain electrical contact with copper leads during rotation. The stepper motor and SCP strings were electrically decoupled to prevent the energizing motor coils from inducing noise in the resistance measurement during actuation.

Experiments were automated with a microcontroller based on the ATmega2560 microchip. A 16-bit ADC (ADS1115, Adafruit) connected to the microcontroller was used to discretize the length measurement captured by an analog magnetoresistive position sensor (SPS-L225-HALS, Honeywell). The position sensor had a resolution of 0.14 mm and a sensing range of 225 mm. The resistance of the TSA was calculated by applying a precise current (50 mA ± 5 μA) from a current source (AD8276, Analog Devices) and measuring the voltage
across the strings. A 20-bit ADC (CS5513, Cirrus Logic) enabled 0.240 μΩ resistance measurement resolution.

B. Experimental Characterization

The chosen input sequence was a series of motor rotation steps at 22 rad/s that twisted and untwisted the TSA. After each step, the motor paused for a specified duration, during which the resistance and length were constantly measured. Five sets of experiments were conducted for the following step durations: 2.4 s, 6 s, 17 s, 32 s, and 98 s. Each set was tested for four cycles, where one cycle included a series of twisting and untwisting steps. The motor rotation input sequence is shown in Fig. 3(a). Each step consisted of five motor rotations and took 1.4 s to complete. The TSAs considered in this study were tested in the range of [15, 30] string twists. The input sequence was chosen to cover the major actuation range [23]. In addition, it was found that the resistance’s transient response would become more complicated when the strings untwist or twist too much – when the TSA was fully untwisted, the strings would become two resistors in parallel, such that each string was less than half of the diameter of the twisted TSA; when the strings were over-twisted, the TSA might form an undesirable coiled structure, making both the length and resistance complicated to predict.

Fig. 3(a) shows the experimental measurements of the transient actuator length and resistance on a logarithmic time scale for a TSA with a 350 g load. During one cycle, the resistance of the TSA was greater at greater lengths and fewer string twists. As the strings twisted more, the TSA decreased in length and increased in diameter. Consequently, the SCP strings were in greater electrical contact, which reduced the resistance. After the motor rotated, spikes in resistance were noticed in the first data point after the motor rotated, as shown in Fig. 3(a). In addition, the strain-resistance measurements exhibited three behaviors, namely, transient decay, hysteresis, and creep.

1) Transient Decay: Experiments showed that the resistance transiently decayed after any amount of string twists and step durations, as shown in Fig. 3(a)-(b). As time increased, the rate of resistance decay decreased until reaching steady-state after approximately two minutes [23]. In addition, the length of the TSA remained constant during this time, as shown in Fig. 3(b). The transient resistance decay might suggest that there was inductance in the SCP strings’ conductive coils. After each rotation, TSA underwent a spike in applied current from 0 mA to 50 mA (this current was necessary to measure the resistance of the twisted SCP strings). In addition, the inductance of a coil generally varies with the square of the number of turns in the coil [27].

2) Hysteresis: Under a symmetric motor rotation input (Fig. 3(a)), the length output was not symmetric (Fig. 3(c)). The quasi-static relationship between resistance and length showed hysteresis, as found in our previous work [23] and shown in Fig. 3(c). In addition, the compliant TSAs in this study were expected to exhibit hysteresis; previous studies have found hysteresis individually in both TSAs and SCP actuators [16], [17], [28]. Hysteresis has previously been revealed in a variety of smart materials, elastic materials, and ferromagnetic materials [29], [30].

3) Creep and Self-Sensing Lifetime: The creep of the resistance measurement was evident as the number of cycles increased, as shown in Fig. 3(d). The length of the TSA demonstrated mild creep within the first ten minutes of the test and then became negligible. The lifetime of the self-sensing property in TSAs was experimentally tested for 596 cycles lasting over two and a half hours. To do so, the TSA was loaded with a 550 g load and twisted in the following manner: After initially twisting the strings 15 twists, the motor rotated for two turns at a time, then paused for one second, repeatedly until the string reached 25 twists. This input sequence was repeated for the entire duration of the test. The creep in resistance over many cycles for other materials has been observed in previous work as well [24]. The cause of creep was perhaps due to the friction between the two SCP strings during twisting. As the strings twisted, the silver coating may have gradually worn off over time to make the strings less conductive. A previous study on the lifetime of TSAs found that the friction and heat contributed toward the deformation and degradation of the strings [28]. However, those experiments were conducted at 2000 rpm, nearly 10 times the speed of the TSA used in this work. In addition, the TSA in [23] was tested at loads between 3-20 kg, which was much greater than the loads used in this study. Due to these reasons, evident temperature increases were not observed. However, the temperature of the strings may likely have increased slightly during the experiments. Measuring the temperature of the TSA is beyond the scope of this study.

III. MODELING

The proposed model to capture the strain-resistance relation is a sum of transient decay, hysteresis, and creep components. When the model is identified, its inversion is used as the self-sensing model to estimate strain based on resistance. This procedure is convenient since the resistance of the SCP strings not only depends on the strain generated by the TSA but also on time, as the TSA exhibits transient decay and creep.
A. Strain-Resistance Model

The resistance of the TSA, $y_{\text{model}}$, can be expressed as the sum of three terms, namely, transient decay, hysteresis, and creep. The overall resistance $y_{\text{model}}$ is written as follows:

$$y_{\text{model}} = y_t + y_h + y_c,$$

where $y_t$ is the transient response of the resistance, $y_h$ is the hysteresis term, and $y_c$ is the creep term. The response not due to transient decay, $y_t$, is modeled with the sum of the resistance due to hysteresis $y_h$ and creep $y_c$: $y_{\text{model}} = y_h + y_c = y_{\text{model}} - y_t$.

1) Transient Decay: While the TSA was at rest (the motor is not rotating), the resistance decayed at a decreasing rate. This behavior is shown in Fig. 3(b). Experiments showed that the length instantly reached its steady state after each rotation of the motor. Therefore, the transient resistance decay does not have a corresponding length decay or increase. It is proposed that the overall resistance is expressed by

$$y_{\text{model}}(t) = b_1 \ln^2(t - t_0) + b_2 \ln(t - t_0) + y_{\text{model}}. \tag{2}$$

where $t_0$ is the instant when the motor stops rotating and $t > t_0$, $y_{\text{model}}$ is the resistance value when $t - t_0 = 1$, $b_1 < 0$ and $b_2 < 0$ are constants to be identified and they are constrained to be negative due to the resistance decay. Note $y_t$, the response not due to transient decay, is estimated by the hysteresis term and creep term to be $y_{\text{model}}$. Therefore, the transient decay $y_t$ is defined as $y_t = b_1 \ln^2(t - t_0) + b_2 \ln(t - t_0)$.

A decaying exponential function was also attempted to model the transient decay. However, it was found that the approach would require different $b_1$ and $b_2$ for each set of experiments with a specific step duration, making it difficult to obtain a generalized model. Therefore, Eq. (2) is adopted in this study where $b_1$ and $b_2$ take the same values for all sets of experiments with different step durations.

2) Hysteresis: A rate-dependent Prandtl-Ishlinskii (PI) model [31, 32] was adopted to capture the hysteresis component of the strain-resistance relationship, to incorporate the motor step input duration that affects the peak-to-peak value of the resistance, as shown in Fig. 3(a). The PI model was chosen over other existing hysteresis models because model inversion will be required for self-sensing (see Section III.B) and the analytical inversion of the PI model can be efficiently obtained [33]. The output $y_h$ of the PI model is a weighted sum of play operators with different thresholds. The play operator,
where $w_i$ and $r_i$ are computed directly from the previously identified parameters of the PI model \[33\]. The output of the play operator $F_{\bar{r}}(k)$ depends on the thresholds $\bar{r}_i$ as follows:

$$F_{\bar{r}}(k) = \begin{cases} \min(o_2(u(k)) + \bar{r}_i, F_{\bar{r}}(k - 1)), & u(k) < u(k - 1) \\ \max(o_1(u(k)) - \bar{r}_i, F_{\bar{r}}(k - 1)), & u(k) > u(k - 1) \\ F_{\bar{r}}(k - 1), & u(k) = u(k - 1) \end{cases} \tag{10}$$

where $o_1$ and $o_2$ are envelope functions given below expressed with hyperbolic tangents, as given in \[32\]:

$$o_1(u(k)) = \rho_0 \tanh(\rho_1 u(k) + \rho_2) + \rho_3, \tag{11}$$
$$o_2(u(k)) = \phi_0 \tanh(\phi_1 u(k) + \phi_2) + \phi_3,$$

where $\rho_0, \rho_1, \rho_2, \rho_3$ and $\phi_0, \phi_1, \phi_2, \phi_3$ are constant parameters to be identified.

IV. MODELING RESULTS

A. General Procedure

The proposed model was identified based on two sets of experiments with step durations of 6 s and 32 s. The model was then validated on three sets of experiments with step durations of 2.4 s, 17 s, and 98 s. The model was identified with the following procedure:

1) Construct an $m \times n$ matrix that contains the experimental resistance values, where $m$ is the number of transient curves and $n$ is the number of sampled points in each transient curve.
2) Obtain an equation of fit for the transient decay $y_i$, by passing each row of the matrix into a curve fitting function. A second-order polynomial relationship between $\ln(t - t_0)$ and transient resistance $y_i$ was identified with the MATLAB function `polyfit`.
3) Store the $m$ values of $y_i = y_{\text{exp}} - y_i$ into a separate vector. $y_i$ will be the input to the creep and hysteresis model.
4) Initialize a vector $X$, whose elements are the model parameters to identify. Let $y_{i,\text{model}}(X)$ be an $m \times 1$ vector that denotes the output of the model due to the parameters contained in $X$. In this study, a nonlinear multivariable function, $f(X)$, was formulated such that:

$$f(X) = \sum_{k=1}^{m} \left(y_{i,\text{model},k}(X) - y_{s,k}\right)^2. \tag{12}$$

By utilizing the MATLAB function `fmincon`, the optimal constrained parameters were identified when $f(X)$ reached a local minimum. The iterative computation stops when the function stops decreasing to within a specified tolerance and specified constraints are satisfied with the specified tolerance as well. If the local minimum yields an error larger than a given threshold, rerun the optimization with different starting values for $X$ to obtain a different local minimum. The interior-point algorithm was utilized \[35\], but other algorithms may also be used.

5) Obtain the strain-resistance model as follows:

$$y_{\text{model}}(k) = y_{s,\text{model}}(k) + y_i(k). \tag{13}$$

6) Finally, the self-sensing model will be obtained through inversion of the strain-resistance model. The input to the
self-sensing rate-dependent PI model is $u(k)$ from Eq. \ref{eq:u}. There are eight additional parameters to identify: $\rho_0$, $\rho_1$, $\rho_2$, $\rho_3$, $\phi_0$, $\phi_1$, $\phi_2$, and $\phi_3$ from Eq. \ref{eq:parameters}. To solve for these parameters, utilize the same strategy from the previous step to minimize the sum of squared differences between the actual and modeled lengths.

**B. Model Identification**

An order of $N_c = 2$ and $N_h = 60$ was chosen for the creep model and hysteresis model, respectively. Further increasing either $N_c$ or $N_h$ negligibly decreased modeling error but increased the computational complexity. For the strain-resistance model, the initial value of $X$ was chosen to contain each ele-
TABLE I
IDENTIFIED MODEL PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Strain-Resistance Model</th>
<th>Self-Sensing Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>$1.27 \times 10^{-2}$</td>
<td>$\phi_0$</td>
</tr>
<tr>
<td>$A_2$</td>
<td>$9.61 \times 10^{-1}$</td>
<td>$\rho_1$</td>
</tr>
<tr>
<td>$c_1$</td>
<td>$-3.69 \times 10^2$</td>
<td>$\rho_2$</td>
</tr>
<tr>
<td>$c_2$</td>
<td>$536.1 \Omega$</td>
<td>$\phi_0$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$-1407.3 \Omega/cm$</td>
<td>$\phi_1$</td>
</tr>
<tr>
<td>$b_1$</td>
<td>$-1.71 \times 10^{-3}$</td>
<td>$\phi_1$</td>
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<tr>
<td>$b_2$</td>
<td>$-2.68 \times 10^{-4}$</td>
<td>$\phi_2$</td>
</tr>
</tbody>
</table>

The overall performances of the self-sensing model and strain-resistance model were provided in Fig. 4(k) and (l), respectively. The model validation error was slightly greater than the identification error. The proposed self-sensing model with a single set of parameters worked for all cases with different twisting steps and step durations. The motor rotations need not be measured, as long as the load remains constant and the string twists stay within the working range of the TSA. It must be known whether the motor is on or off, as this determines whether or not the resistance transiently decays.

V. CONCLUSION AND FUTURE WORK

In this work, the self-sensing property of compliant TSAs was experimentally characterized and modeled. The nonlinear relationship between the strain and resistance was characterized through a series of experiments, and a self-sensing model was proposed to estimate the strain of the TSA based on its resistance. The proposed model consisted of a log-based polynomial term, a rate-dependent PI hysteresis term, and a creep term.

Despite the high accuracy of the proposed self-sensing model, a more generalized model will be developed in future studies. Since the model in this study only considered a constant loading condition, future studies would also account for different or even dynamic loads on the TSA. A preliminary experiment on the load-dependence of resistance showed that the load significantly affected the magnitudes of the hysteresis term of the resistance, but not the creep and transient decay. This is likely because increased loads (1) longitudinally stretch the TSA and (2) decrease the diameter of the TSA. In future work, each component of the model will be separately examined for its dependence on load. The findings of this study may potentially apply to other conductive materials that experience similar transient resistance decay [23]–[26]. Future work will also use the resistance as a feedback signal to control the length of the TSA.

Using resistance for strain estimation has two main advantages over motor encoders: When the TSA is constructed with stiff strings or only operates under a constant load, this strategy enables smaller DC motors without encoders to be utilized, which may result in reduced weight or mechanical complexity. More importantly, resistance sensing is advantageous when the TSA’s strings are compliant or under varying loading conditions. A varying loading condition that stretches or shortens such TSA would be accompanied by a change in resistance, but not a change in motor angle. In future work, experiments will be conducted to predict both load and strain, given the resistance and twisting angle. This prediction may be realized by simultaneously solving two equations: the TSA dynamic model [9], [10] and strain–load–resistance model.
Our previous work showed that compliant TSAs could generate large strain when they were twisted and then heated [23]. In the future, the proposed self-sensing model will be further improved to estimate the length of these TSAs also during thermal actuation. The potential coupling between resistance and temperature may present new challenges. In the meantime, the length of TCP-based TSAs actuated by only twisting can be accurately predicted via the resistance.

REFERENCES