Development of a Fabrication Setup for Producing Super-coiled Polymer Actuators

Cagri Hindistan[1], Erman Selim[1], Enver Tatlicioglu[1], Yavuz Ozturk[1]

Abstract— **This study addresses the modeling, fabrication, and experimental characterization of super-coiled polymer (SCP) actuators. Initially, the modeling approaches available in the literature are examined, with a focus on thermo-mechanical and thermo-electrical models used to describe dynamic actuator behavior. Subsequently, the equipment required for actuator fabrication is designed and manufactured in order to obtain a standardized production process. In particular, a winding mechanism was developed to produce nickel-wrapped fishing line structures with adjustable winding ratios. Based on the developed fabrication setup, SCP actuators were produced and their actuation responses were investigated experimentally. The experimental results provide insight into the behavior of the fabricated actuators and show that the proposed setup can be used effectively for standardized production and experimental investigation of SCP actuators.**

I. Introduction

Over the past few decades, significant advances have been made in the development of soft robots and their wide-ranging applications, including medical devices [1] , human-centered grasping and manipulation [2], and field exploration [3]. Compared with conventional robots with rigid links, soft robots offer distinct advantages due to the elasticity and compliance of the deformable materials from which they are constructed. Soft actuators, such as shape memory alloys [4], [5], [6] and super-coiled polymer (SCP) actuators [7], [8], have attracted considerable attention in recent years because of their potential to enable safer interaction with the surrounding environment [9], [10]. Among these, SCP actuators have a wider range of applications such as different robotic systems such as artificial muscles [11], soft gripper [10], and robotic eye [12], [13], [14], than standard actuators due to their ability to perform elongate and contractions movements in addition to rotational and linear movements.

SCP actuators can function as actuators by expanding and contracting when heated and cooled, respectively, in addition to conventional actuators. However, despite their wide range of applications, this characteristic makes their use as actuators challenging. In addition to the difficulty of use, the production of SCP actuators is also one of the challenging aspects. Review of the relevant scientific literature reveals that there are different methods for producing SCP actuators. While the choice of materials, such as the type of soft material and conductor used for SCP production, is very important, it is also crucial to standardize these materials to produce them as actuators. SCP actuators may be produced from different polymer-based yarns or filaments, including Spandex yarn [15], nylon sewing threads, and fishing lines [16]. In [17], a SCP actuator was fabricated by winding a conductive sewing thread around a helical mandrel. In [15], a silver wire paste coating was applied to the surface of the actuator and heated through the Joule effect. In this approach, wrapping a conductive wire around or through the SCP enables a more uniform distribution of heat. As a result, each region of the SCP can undergo elongation and contraction more uniformly, providing an advantage in measurement accuracy. In [8], SCP artificial muscles were fabricated using commercially available yarns. These yarns are silver-plated, allowing them to be electrically actuated by generating heat when an electric current passes through them. Specifically, Shieldex silver-plated cotton nylon yarns were used for the fabrication of the SCP artificial muscles. In [18], the actuators were made from Nylon 6.6 conductive sewing thread. In [10], a SCP actuator was fabricated using multi-filament materials. Unlike mono-filament-based actuators, the fabrication process requires careful temperature control to achieve the desired length for the SCP actuator. For this purpose, Joule heating, generated by passing electric current through the metal wire wound around the SCP actuator, was employed, as it is more practical than conventional heating methods such as water baths and hot air. In [11], the conductive thread was super-coiled by attaching one end of the thread to a motor and suspending a weight from the other end to maintain tension during twisting. A 50 g weight was used for the $117/17$ thread. The thread was twisted at a low rotational speed in the direction of its original twist until coils formed along its length. Fully coiled structures were obtained at 392 ± 15 rotations/cm (post-coiling length). After coiling, the thread was folded back onto itself to form a two-ply configuration, which helped prevent unwinding.

In addition to fabrication and application studies, the modeling and control of SCP actuators have also attracted considerable research interest. Nevertheless, the motion control of these actuators is still difficult because reliable dynamic models are not yet well established [19]. Therefore, recent research has been devoted to obtaining mathematical models of SCP actuators. In [20], three types of bundled SCP actuators were designed and fabricated for force amplification. Their characteristics were experimentally investigated by measuring and comparing the force, strain, and dynamic properties of the actuators with different bundle configurations. In [21], least squares-based parameter estimator was developed for

[1]C. Hindistan, E. Selim, E. Tatlicioglu, and Y. Ozturk are with Department of Electrical & Electronics Engineering, Ege University, 35040, Bornova, Izmir, Turkey cagri.hindistan@ege.edu.tr, erman.selim@ege.edu.tr, enver.tatlicioglu@ege.edu.tr, yavuz.ozturk@ege.edu.tr

the thermo-mechanical and thermo-electrical model of a SCP actuator, with the aim of eliminating the need for acceleration measurement.

This study aims to investigate SCP actuators from modeling, fabrication, and experimental perspectives. In this work, the modeling of SCP actuators is presented, and the design and fabrication of the equipment required for their production are described in detail. Subsequently, SCP actuators are fabricated using the developed setup, and their actuation responses are examined experimentally.

The main innovative aspects of the proposed study are as follows:

- Comprehensive treatment of SCP actuators: This paper addresses SCP actuators from a unified perspective by combining modeling, fabrication, and experimental investigation within a single study, rather than focusing on only one aspect of these actuators.
- Systematic presentation of the fabrication process: In addition to discussing SCP actuator models, the paper provides a clear and structured description of how SCP actuators are manufactured, thereby improving the practical reproducibility of the study.
- Development of custom fabrication equipment: A key novelty of this work is the design and development of dedicated machines/equipment for SCP actuator production. This aspect extends beyond conventional modeling and testing studies and highlights a practical contribution that has received limited attention in the existing literature.

The rest of the paper is outlined as follows. In Section II, the mathematical models of the SCP actuators are presented. In Section III, the SCP actuator production method is presented in a detailed manner. In Section IV, preliminary experimental results are provided. Finally, in Section V, concluding remarks are given.

II. System Models

Review of the relevant scientific literature indicates that the models of SCP actuators are generally presented in two subsystems, namely thermo-mechanical and thermo-electrical. It is further observed that a variety of experimental methods have been employed in the derivation of these models. Although a unified mathematical model for SCP actuators has not yet been established in the literature, several different modeling approaches have been proposed.

One of the models used in the scientific literature for an SCP actuator that produces uniaxial translational motion in response to temperature variation is presented as follows [10]

$$m\ddot{x} + b\dot{x} + k(x - x_0) = c(T - T_0) \quad (1)$$

$$C_{th}\dot{T} = -\lambda(T - T_0) + \frac{1}{R}V^2 \quad (2)$$

where (1) represents the thermo-mechanical model, whereas (2) denotes the thermo-electrical model. The variables $x(t)$, $\dot{x}(t)$, and $\ddot{x}(t)$ represent the displacement, velocity, and acceleration of the SCP actuator, respectively, $T(t)$ denotes the actuator temperature, and $V(t)$ represents the voltage applied to the actuator. In the thermo-mechanical model given in (1), m denotes the total mass of the actuator, including the attached load; b is the damping coefficient; k is the spring stiffness of the actuator; and c is a parameter that characterizes the effect of temperature on the system. Moreover, x_0 represents the initial length of the SCP actuator, and T_0 denotes the ambient temperature. In the thermo-electrical model presented in (2), C_{th}, λ, and R represent the thermal mass, thermal conductivity, and electrical resistance, respectively.

In [22], to describe the behavior of the SCP actuator, the authors considered the following nonlinear model

$$m\ddot{x} + \left(b + b_1\dot{x}^2\right)\dot{x} + \left(k + k_1x^2\right)x + a_1(T - T_0) + a_0 = F \quad (3)$$

where, k_1 and b_1 denote the nonlinear stiffness and damping coefficients, respectively, whereas a_1 represents the modeling uncertainties associated with c, and a_0 is a coefficient accounting for the constant offset in the model. In the study of [22], this model was employed to capture the nonlinear characteristics of the actuator in a more accurate manner. Considering (3), it can be stated that, unlike linear spring and damper models in (1), nonlinear spring and damping characteristics are taken into account, and the uncertainties in the driving force appearing on the right-hand side of (1) are also incorporated into the model.

In order to capture the nonlinear characteristics of horizontally actuated spandex-nylon SCP actuators, via acknowledging a second-order temperature-force relationship, the work of [15] proposed the following mathematical model

$$m\ddot{x} + (b + \alpha_1(T - T_0))\dot{x} + kx = F \quad (4)$$

where α_1 is a constant model parameter, and $F(T) \triangleq c(T - T_0)$ denotes the driving force in the thermo-mechanical model. A comparison of (1) and (4) indicates that, in (4), the damping coefficient is modeled as a function of the actuator temperature, whereas in (1), it is assumed to be constant.

III. SCP actuator Production

SCP actuators are composed of a polymer-based material, and an electric current is passed through a conductor to heat the polymer. After testing different conductive materials, nickel was determined to be the most suitable choice. For the fabrication of the SCP actuator, a conductive nickel wire is wound around the fishing line. A 3D design of the machine developed to standardize the SCP actuators produced through this process is presented in Fig. 1. The fabricated version of the nickel–fishing line winding machine designed in Fig. 1 is presented in Fig. 2. The fabricated machine incorporates two stepper motors. The first stepper motor provides linear motion along the aluminum profile, whereas the second stepper motor generates rotational motion, thereby enabling the nickel wire to be wound around the fishing line. By adjusting the speed ratio between the two motors, nickel–fishing line pairs with different winding ratios can be obtained. This makes it possible to characterize the behavior of SCP actuators manufactured with different winding ratios. A representative nickel–fishing line pair produced through

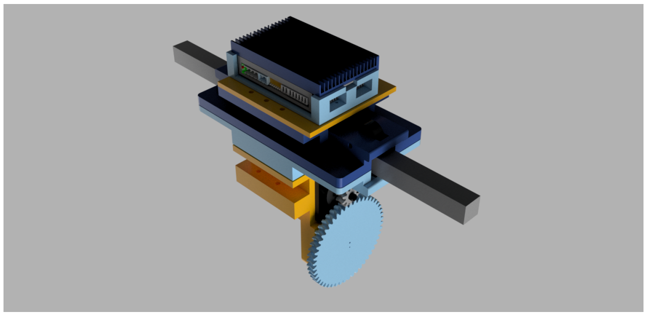

Fig. 1: Computer aided design of nickel-fishing line winding machine

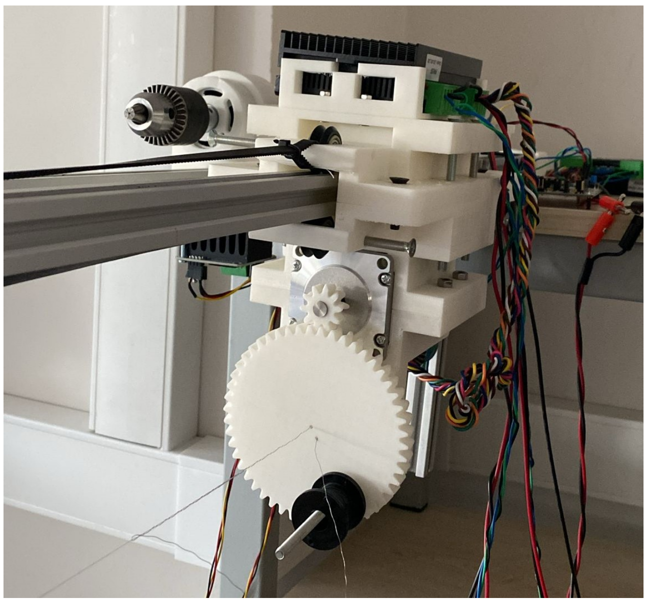

Fig. 2: Manufactured nickel-fishing line winding machine

this process is shown in Fig. 3. Following this process,

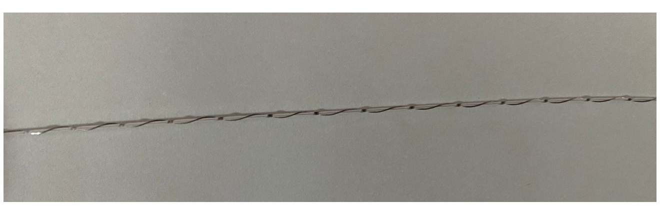

Fig. 3: A sample of produced nickel-fishing line wire

the fabricated material is attached to the end of the DC motor shown in Fig. 4 and to the linear carriage. Tension in the material is maintained by means of a counterweight suspended from the carriage. As the DC motor rotates, the material gradually compresses while undergoing twisting. After a certain threshold is reached, it self-coils, leading to the formation of the structure referred to as an SCP actuator, as illustrated in Fig. 5.

IV. Experimental Studies

In this section, the fiber optic-based displacement sensor used to measure the displacement of the SCP actuator was

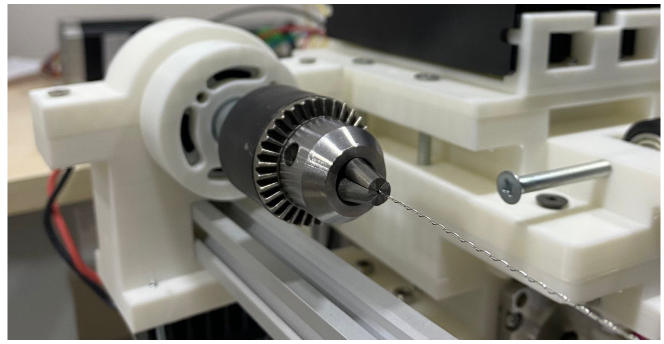

Fig. 4: Wire twisting machine

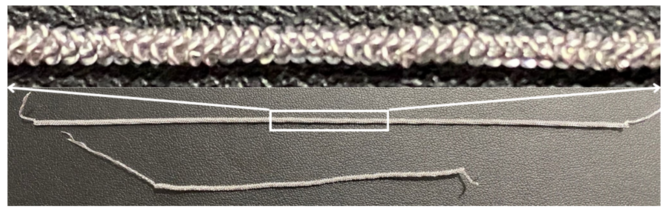

Fig. 5: A fabricated SCP actuator

experimentally investigated under different reference inputs. In this test setup, a ZT06 thermal camera is also used to measure the temperature of the actuator. The voltage to be applied to the SCP actuator is generated in the MATLAB/Simulink environment and transmitted via a USB communication line to the STM32F746ZG microcontroller. Based on this transmitted reference information, a PWM signal is generated through the BTS7960B motor driver and applied to the SCP actuator. Due to the operating characteristics of the SCP actuator, as the applied voltage increases, the current flowing through the nickel wire also increases. This increase in current causes the actuator to heat up through Joule heating, resulting in its contraction. Consequently, the electrical input applied to the SCP actuator is converted into a mechanical actuation response.

A. *Step Input Reference*

In this sub-section, the response of the produced SCP actuators was investigated where a step input was applied to the open-loop system. In this case, the expected behavior for the SCP actuator was to respond in accordance with the applied step input. The experiment was repeated twice using the same step input. With each new step, the voltage applied to the SCP actuator increased, which in turn caused the current to increase. The increased current heated the SCP actuator and caused it to contract. As a result, the mirror attached to the SCP actuator was expected to move away from the fiber source. The motion of the SCP actuator in response to the step input can be observed in Fig. 6. In Fig. 6, the step input voltage applied to the system and the corresponding position data obtained from the sensor are presented together. The left axis represents the applied voltage, while the right axis indicates the position information measured by the sensor. During the experiment, the input voltage was increased in a stepwise manner; approximately 0 V was applied during the 0–50 s interval, 7.5 V during 50–100 s, 10 V during 100–150 s, and 11.5V during 150–200 s. In response to these voltage increments, an increasing trend was observed in the sensor output. Although the measured position data contain noise and small-amplitude fluctuations, the system is seen to respond consistently to the step changes in the input voltage. As expected, the increase in voltage leads to an increase in current, which in turn causes the SCP actuator to heat up. Fig. 7 shows a thermal image captured during the experiment

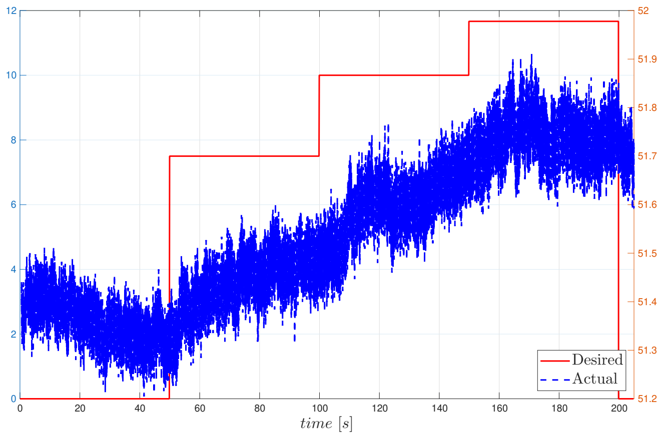

Fig. 6: Desired and actual position

through the thermal camera application. The yellow region corresponds to the SCP actuator, and a box was drawn around this area so that the maximum and minimum temperatures within the region could be measured and read in MATLAB. As the mirror moves away from the fiber source, the voltage

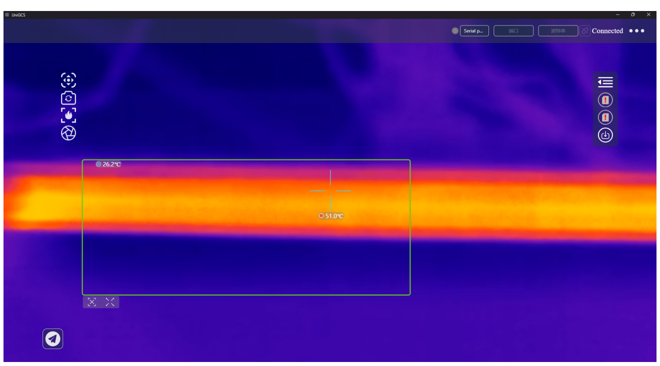

Fig. 7: Thermal camera image

is expected to decrease. As shown in Fig. 8, a decrease in voltage can indeed be observed. Fig. 9 shows the temperature variation measured by the thermal camera. It can be observed that the temperature also changes in response to the step input.

V. Conclusions

This study presented a comprehensive investigation of SCP actuators from modeling, fabrication, and experimental perspectives. First, the modeling approaches reported in the

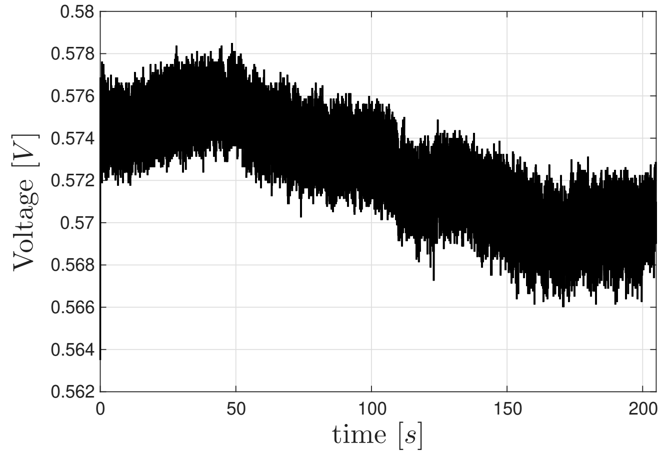

Fig. 8: Voltage change in response to the step input

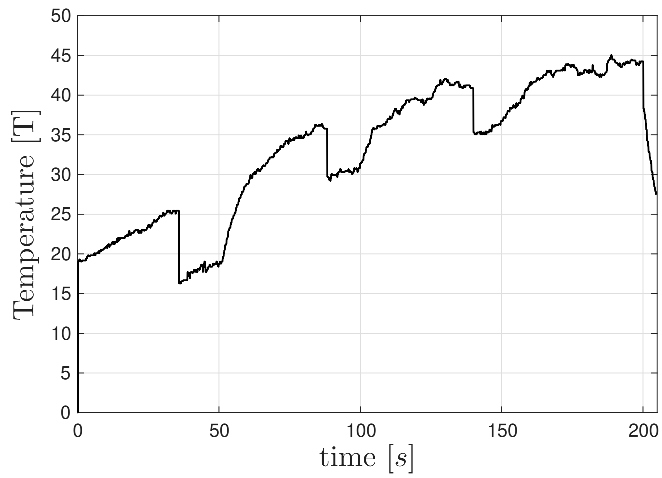

Fig. 9: Temperature change in response to the step input

literature were reviewed, with particular emphasis on thermo-mechanical and thermo-electrical models used to describe actuator behavior. Then, the equipment required for SCP actuator fabrication was designed and manufactured to establish a more standardized production process. In particular, a winding mechanism capable of producing nickel-wrapped fishing line structures with adjustable winding ratios was developed. Using the proposed setup, SCP actuators were successfully fabricated and experimentally characterized. The experimental results provided insight into the actuation behavior of the fabricated actuators and demonstrated that the developed fabrication system can be effectively used for the standardized production and investigation of SCP actuators. Overall, the study contributes both a practical fabrication framework and an experimental basis for future research on the design, modeling, and applications of SCP actuators.

As a possible continuation of this study, future work will focus on the implementation and evaluation of closed-loop control algorithms for SCP actuators. In particular, different control strategies will be investigated to improve positioning accuracy, response characteristics, and robustness against thermal and mechanical disturbances. In addition, the integration of the developed fabrication setup with sensing and feedback mechanisms may enable more precise experimental analysis and more reliable actuator performance. These studies are expected to contribute to the practical use of SCP actuators in controlled actuation applications especially in the field of soft robotics.

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