Modeling, Characterization and Control of a Novel Torsional Shape Memory Alloy (SMA) Actuator

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Abstract—Thermally activated shape memory alloy (SMA) actuators are direct-driven and produce high power density with design versatility. However, beyond their linear actuation in spring forms there is little variety and their application in robotics is limited by the challenging characterization of the actuator. In this paper we introduce a novel low-profile torsional SMA actuator design, and its comprehensive mechanical performance characterization for centimeter-scale robotic applications. We determine the thermo-mechanical model of the actuator with full characterization experiments with load, without load, and in blocked conditions to analyze actuator performance in robotic applications. We also illustrate its application in an origami robot with closed-loop control of the actuators. From the performance tests we have modeled and demonstrated the functional capacity of this low weight torsional actuator and have possibly shown the maximum physical and material limits of an SMA that produces 34.1 mNm torque and has a torque-to-weight ratio of 486 mNm/g.

I. INTRODUCTION

Shape Memory Alloy (SMA) made of nickel and titanium compound (nitinol), has received wide interest from both research and industry due to its intelligent nature of memorizing shape and its high force output. Different types of SMA torsional actuators have been developed such as helical torsion spring [1], twisting wire [2], twisting strips [3], thin sheet torsional actuators [4] as well as antagonistic arrangements of multiple wires [5] for reversible motion, as an alternative to bulky electric drives. Torsional actuators are useful for applications concerning large angular displacements in modular and self-reconfigurable robots [6], surgical tools [7], morphing wings [8] as well as in the field of robotic origami or Robogami [9]. Origami robots are intelligent quasi-2D platforms with multiple tiles that can be reconstructed into 3D shapes in a certain folding sequence [10]. In Robogami applications, actuation plays an important role in achieving desired shape transformations. Besides having a miniature size and high range of folding angle (≈ 180°), actuators should generate sufficient torque for lifting multiple tiles and perform motion in loaded conditions. In order to attain the desired shapes, folding angles should be controllable; control challenges exist not only due to the undesired non-linear characteristics of SMA but also the need for integration of appropriate on-board angular sensors for feedback at each fold. Conventional solutions using digital encoders remain unfeasible at this scale. Therefore miniature and low weight sensors need to be studied for accurate angle feedback. Moreover, power consumption is another concern with SMA actuators that becomes more significant as the number of actuators grows, thus low power solutions could alleviate these challenges.

The performance of the SMA actuators is primarily related to their metal composition and geometry. For instance, for the SMA torsion coil spring actuator, which is a common actuator, the number of turns dictates its range of motion, while the diameter of the wire defines the output torque. SMA wire with larger diameter can generate higher torques compared to thinner ones; however, it draws higher current due to its lower resistance, related mainly to the cross-sectional area [11]. This is also true for thin sheet [12], strip [3] or other SMA actuators that are activated by Joule heating [13] [14]. Besides Joule heating, it is possible to activate SMA actuators by heat convection employing heating chambers or ovens [3]. Although this method is useful for characterization of the actuators, it is impractical for applications concerning selective activation of multiple actuators. An alternative activation method was proposed in [4] by employing additional heater elements along with the SMA torsion sheet actuator and activating by thermal conduction, which significantly improves power efficiency. Unlike with Joule heating, the heater layer does not act as a short circuit, therefore the input power can simply be controlled by regulating the input voltage with no need for additional current amplifier electronics. Moreover, it allows heat at specific locations, making it an effective activation method for multi-actuator systems.

Despite the extensive ongoing research on SMA there are also challenges in modeling thermo-mechanical characteristics of SMA since the material exhibits high non-linear hysteresis, essentially induced by temperature dynamics and stress [15]. Available constitutive models attempt to explain the thermal and mechanical relations along with SMA material properties. One of the most popular models is Tanaka’s model [16], which considers phase transformation as an exponential function, whereas Liang-Rogers [15] improves the transformation term by replacing it with a cosine function. The detwinned martensite case is further formulated by Brinson [17]. However, no model can relate temperature, load, and actuator geometry unless experimentally characterized.

Table I summarizes the available types of SMA-based torsion actuators in the literature without an antagonistic pair; their performance and the activation method is compared to the novel Omega (Ω) SMA torsional actuator we present in this paper. While the available actuators face challenges in certain aspects we discussed earlier, our Ω-SMA actuator, with its special design and micro-heater layer, outperforms the existing actuators. Given its miniature size, low weight of 0.07 g and
absorbing only 0.5 W of power, it has a high range of motion and a relatively high torque output of 34.1 mNm, with a torque-to-weight ratio of 486 mNm/g; filling the gap of trade-off between size, efficiency, range of motion and output torque.

This paper focuses on the modeling, characterization and control of the novel actuator and its implementation into a multi-tile robotic origami. Our Ω-SMA actuator is used for motion in one direction that can also be extended to bidirectional motion with an additional antagonistic actuator [18] or elastic bias element. The main contributions of this research are:

- A novel low-profile SMA torsion actuator with high torque output and low power consumption;
- Analytical modeling of the Ω-SMA torsional actuator;
- Characterization of the actuator in terms of temperature, position, velocity and torque in three different loading conditions both by experiments and validation of the model;
- Closed-loop control of the actuator by integrating thin film strain sensors for position feedback;
- Experimental and modeling results via closed-loop control of the Robogami prototype.

II. ACTUATOR DESIGN AND FABRICATION

The proposed actuator is made of a thin sheet of Ni50Ti50 SMA (M alloy Memry GmbH) with 0.1 mm thickness. Its low-profile, slim, Ω-like shape has dimensions $12 \times 8 \times 2.5 \text{ mm}^3$ which closes upon heating as depicted in Figure 1a. It is possible to achieve approximately 180 $\text{°}$ of deflection if one end of the actuator is fixed and the other end is kept in plane at an angle of 0 $\text{°}$. The cylindrical hinge forms a circular curvature with a higher circumference compared to “U” geometry obtained by bending; resulting in a higher surface area for activation, a higher range of deflection and torque output and further the life-time of the actuator is prolonged [18]. Likewise, deformation of a “U” shaped metal sheet to its initial flat form is not possible due to plastic deformation of the material that forms certain curvature at the hinge. Therefore, introducing curvature adds an advantage as well as extra elasticity while resetting the actuator to its initial open configuration.

The fabrication and training process of the actuator consists of three steps: first, an unprocessed SMA sheet is cut in a rectangular form with holes using a laser micro-machining station (LAB 3550 Inno6 Inc.). The machined sample is then bent along a 2 mm-diameter steel rod forming a “U” shape. Both ends are squeezed together afterwards so that the rod remains tight within the hinge and the ends are clamped between two jig plates with grooves using bolts and nuts (see Figure 1c). Finally, the assembly is placed into a high temperature furnace (Nabertherm GmbH) and annealed at 400 $\text{°C}$ for 30 minutes to induce the shape.

We use customized micro-heaters to concentrate the thermal activation zone as depicted in Figure 1d. The heaters are made of Inconel-polyamide (Kapton backed Ni-Cr alloy) thin film layer, fabricated to provide heat to the actuator (see Figure 1d). They have multiple resistive paths, patterned in parallel to generate heat upon current flow. This mesh design adds high flexibility to the film when folded or stretched, with negligible loading impact on the actuator. Placing the heater inside the actuator hinge as in Figure 1b, with the kapton side facing the actuator, permits heat transfer by thermal conduction. It is crucial that it adheres to the actuator shape and maintains surface contact for fast and efficient heat conduction. In this configuration, measurement of the actuator temperature is realizable from the outside surface of the Omega-SMA.

### Table I

<table>
<thead>
<tr>
<th>Actuator type</th>
<th>NiTi material</th>
<th>$l \times w \times h$ (mm)</th>
<th>Activation and power</th>
<th>Range (deg)</th>
<th>Torque (mNm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torsion coil spring [1]</td>
<td>wire d=0.5 mm</td>
<td>$10\times7.2\times7.2$</td>
<td>Joule heating, I not spec.</td>
<td>138</td>
<td>0.7</td>
</tr>
<tr>
<td>Torsion coil spring [11]</td>
<td>wire d=1 mm</td>
<td>$4\times5\times5$</td>
<td>Joule heating, 5 A</td>
<td>120</td>
<td>350</td>
</tr>
<tr>
<td>Twisting wire [13]</td>
<td>wire in PDMS d=0.2 mm</td>
<td>$70\times15\times3$</td>
<td>Joule heating, 1.25 A</td>
<td>68</td>
<td>4</td>
</tr>
<tr>
<td>Bending wires in parallel [14]</td>
<td>wire d=0.5 mm</td>
<td>$80\times22\times1.6$</td>
<td>Joule heating, 1.25 A</td>
<td>40</td>
<td>55</td>
</tr>
<tr>
<td>Twisting strip [3]</td>
<td>strip t=0.25 mm</td>
<td>$20\times25\times0.25$</td>
<td>Heating chamber</td>
<td>180</td>
<td>70</td>
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<tr>
<td>Torsion by linear motion [12]</td>
<td>sheet t=0.05 mm</td>
<td>$17\times40\times2.85$</td>
<td>Joule heating, 1.25 A</td>
<td>120</td>
<td>3.75</td>
</tr>
<tr>
<td>Y-shape torsion sheet [4]</td>
<td>sheet t=0.1 mm</td>
<td>$11\times7\times1.5$</td>
<td>Heater coil 0.19 A 13 V</td>
<td>180</td>
<td>4.5</td>
</tr>
<tr>
<td>Bidirectional torsion sheet [19]</td>
<td>sheet t=0.1 mm</td>
<td>$5\times7\times2.5$</td>
<td>Heater print-on 0.22 A 0.33 V</td>
<td>180</td>
<td>4.2</td>
</tr>
<tr>
<td>Ω-SMA torsion sheet</td>
<td>sheet t=0.1 mm</td>
<td>$12\times8\times2.5$</td>
<td>Micro-heater 0.13 A 3.7 V</td>
<td>180</td>
<td>34.1</td>
</tr>
</tbody>
</table>

![Fig. 1.](image-url) The Ω-SMA actuator is set to open configuration at room temperature and it closes when thermally activated (a). The actuator and flexible micro-heater layer assembly (b), clamping jig plates for annealing (c), and laser machined heater and actuator after annealing process (d).
III. Ω-SMA Actuator Modeling

In this section we provide the analytic model of the Ω-SMA actuator, relating bending equations and the thermo-mechanical behavior of the SMA sheet.

A. Geometric model

For the Ω-SMA actuator, the curvature length of the hinge is much larger than the actuator thickness, therefore bending can be considered as pure bending. The strain, stress and the bending angle are given by:

$$\epsilon = \frac{y_0}{C_1} \tan \left( \frac{y}{x} \right), \quad \sigma = \frac{2}{w t^2} \tau$$

where $\epsilon$ and $\sigma$ are the strain and stress, $\theta$ is the bending angle of the actuator moving arm on the $x-y$ Cartesian coordinate plane, $y_0$ is the distance from neutral plane, $l$ is the hinge curvature length, $\tau$ is the torque equivalent to moment generated by each infinitesimal layer on the hinge, $w$ and $t$ are the width and thickness of the actuator, respectively.

B. Thermo-mechanical model

We have adopted the Liang-Rogers SMA constitutive thermo-mechanical model [15] due to its relatively high accuracy in predicting material behavior. The one-dimensional model of SMA is given by:

$$\sigma - \sigma_0 = E(\epsilon - \epsilon_0) + \Omega(\xi - \xi_0) + \Theta(T - T_0)$$

where $E$ is the Young’s modulus, and $\Omega$ and $\Theta$ are the transformation and thermal expansion coefficients respectively. $\sigma$, $\epsilon$, $\xi$, $T$ are the stress, strain, martensite volume fraction and temperature with their initial conditions $\sigma_0$, $\epsilon_0$, $\xi_0$, $T_0$, respectively. (2) can be further simplified by omitting the thermal part since strain caused by thermal expansion is much smaller than that of phase transformation. For a shape memory alloy material, Young’s modulus changes with phase transformation and is given by:

$$E = \begin{cases} E_M & \text{if } \xi = 1 \\ E_A & \text{if } \xi = 0 \end{cases}$$

here, $E_M$ and $E_A$ are the elastic modulus of the SMA at full martensite and full austenite phases, respectively. The phase transformation coefficient can be expressed as $\Omega = -\epsilon_L E$ where $\epsilon_L$ is the maximum recoverable strain. By substituting strain and stress expressions in (1) into (2), the model relating torque to material properties can be written in the following form:

$$\tau = \frac{C_3}{C_1} E (\theta - \theta_0) - C_3 \epsilon_L E \xi$$

where $\theta_L$ is the maximum recoverable angle and $C_3 = C_1/C_2$. In an unloaded condition ($\tau = \tau_0 = 0$) with initial phase at full martensite, the bending angle can be computed from (3) as:

$$\theta = \theta_0 + \theta_L (\xi - 1)$$

$E_A$ and $E_M$ can be computed by:

$$E_A = C_3^{-1} \frac{\tau_{max}}{\theta_0}, \quad E_M = C_3^{-1} \frac{\tau - \tau_0}{\theta - \theta_0}$$

and the stress induced coefficients $C_A$ and $C_M$ can be computed for both heating and cooling processes ($M \rightarrow A$ and $A \rightarrow M$) respectively by:

$$C_A = \frac{E_A}{A_f - A_s}, \quad C_M = \frac{E_M}{M_s - M_f}$$

Finally, the martensite fraction composition is given as cosine functions during the phase transformation from martensite to austenite and austenite to martensite in the following form:

$$\xi = \begin{cases} \frac{1}{2} \cos \left[ a_A \left( T - A_s - \frac{C_2}{C_2^*} \tau \right) \right] + \frac{1}{2} & M \rightarrow A \\ \frac{1}{2} \cos \left[ a_M \left( T - M_f - \frac{C_1}{C_1^*} \tau \right) \right] + \frac{1}{2} & A \rightarrow M \end{cases}$$

where the material constants $a_A = \frac{\pi}{A_f - A_s}$ and $a_M = \frac{\pi}{M_s - M_f}$. Here, $A_s$, $A_f$, $M_s$, $M_f$ are the austenite start, austenite finish, martensite start, martensite finish temperatures, $a_A$ and $a_M$, are the austenite and martensite material constants, respectively. These eight parameters along with $E_A$ and $E_M$ values can be determined through characterization experiments.

IV. Actuator Characterization

Actuator choice requires a full understanding of the mechanical performance. We have thoroughly examined the Ω-SMA actuator for its response in various thermal and mechanical conditions. Experiments in this paper, shows three testing conditions: no load, applied load, and blocked load conditions. The unloaded tests define $A_s$ and $A_f$ temperatures of the actuator. The material elastic coefficient $E_M$ and stress induced coefficient $C_M$, can be determined by loading the actuator at room temperature, where $E_A$ and $C_A$ are characterized by a blocked test at $T > A_f$. Two test setups were designed for this purpose; the setup for angular rotation measurement at no load and the force measurement setup for loading conditions. In free rotation (see Figure 2(a)), two small rectangular tiles are mounted onto the actuator at both ends. The glass fiber-reinforced layer, fabricated via micro-laser machining system has an extremely low weight, alleviating load. In this arrangement, one of the arms is clamped and kept stationery while the other arm can rotate freely along the actuator torsion trajectory. Red mark on the moving arm enables tracking of the angular deflection of the actuator arm using a video camera (Nikon D3100) placed above the actuator axis of rotation while an IR thermal imaging camera (FLIR A35) is pointed at the back surface of the actuator hinge to measure its temperature. A microcontroller (Arduino Nano) is used for adjusting the level of the input power by PWM duty cycle modulation. A power source of 3.7 V DC output is connected to a transistor switch. The transistor is switched by the PWM signal from the microcontroller. Hence with this method, desired power
flow to the micro-heater layer can be regulated in an efficient manner since the input power is directly proportional to the PWM duty value.

The force measurement apparatus depicted in Figure 2(b) consists of two rectangular metallic plates forming a closing or opening hinge. Similar to the previous arrangement, one of the arms is kept stationary and mounted on the high precision force sensor (Nano17 ATI Industrial Automation) while the moving arm is mounted on the moving plate driven by a DC motor with an embedded encoder (A-max16 Maxon Motor AG). The motor in the setup can be positioned at the desired angle using the commercial controller board (ESCON 36/2 DC, 4-Q Servocontroller). SMA loading can be performed by driving the motor at constant rate and blocked torque tests can be realized by halting the motor at various angles and activating the actuator. Here, real-time temperature measurement is performed employing the same thermal camera described in the first setup and force is measured using load cell and position data of the DC motor provided by the encoder.

A. Free rotation with no load

We employed load-free angle-temperature measurement to determine \( A_s \) and \( A_f \) temperatures by heating the actuator with no load applied, and \( M_s \) and \( M_f \) temperatures in the cooling process of the actuator. The torque-free test setup is utilized and the procedure is as follows: first the actuator is manually set to open configuration at room temperature as in Figure 2(a), then the heater is activated by giving input power and the actuator moves to a closed configuration. The video camera placed above the actuator captures the torsional angle of the actuator while the thermal camera concurrently records the hinge temperature. Different input power levels are tested in order to study power influence on actuator response time. Figure 4 shows the actuator angular displacement for three different input power levels, 4a, and the corresponding measured temperature for each case 4b. Here, the actuator is activated until a closed configuration is reached then cooled down using a PC fan. The fan is employed to expedite the experimental process and does not alter actuator’s \( M_s \) and \( M_f \) characteristic temperatures. However, for robotic applications with multiple actuators in the system, natural cooling can be considered with slower cooling rate which in our case was approximately 50 % slower than the cooling rate with the fan. From 4a it is noticeable that the slope of the data curve steepens with higher power inputs since higher power increases the activation rate. This is even more evident when we deduce the velocity information given in Figure 4c by differentiation and filtering the angle data given in 4a. For each input power, the cooling process that involves turning off the heater and turning on the fan is initiated after full closed configuration of the Omega-SMA. Input temperature and output angular deflection for heating and cooling processes is summarized in Figure 4d.

The maximum angle of deflection for heating is measured at \( \theta = 132 \, ^\circ \) due to mechanical constraints introduced by the screws used to mount the actuator-heater layer to the glass fiber tiles. The screw heads from both ends of the actuator make contact while closing. The maximum recoverable angle is measured at \( \theta_L = 102 \, ^\circ \) after cooling.

The experimental plot for heating and cooling processes along with the calculated model is given in Figure 4a. Experimenental data for input power \( P = 0.37 \, \text{W} \) is considered in this case. Approximate values of \( A_s \) and \( A_f \) are evaluated from the experimental plot for heating process (\( M \to A \)) where \( M_s \), \( M_f \) and \( \theta_L \) values are determined from the cooling procedure (\( A \to M \)). These parameters are employed to compute the analytic relation in 4. Since this test considers no effect of load, stress-induced terms in the martensite volume fraction for phase transitions can be omitted by setting \( C_A \tau = C_M \tau = 0 \), and \( T \) is taken as the actual measured temperature of the actuator for \( P = 0.37 \, \text{W} \). As a result, the model complies relatively well with the experimental results with maximum deviation of 11.3 %. \( A_s \), \( A_f \), \( M_s \), and \( M_f \) values obtained from the model fit are summarized in Table II.

B. Blocked torque test for \( T > A_f \)

The blocked torque test determines the maximum torque \( \tau_{\text{max}} \) generated by the actuator at \( T > A_f \). In this test, we performed blocked force measurements at different angles and then torques are calculated by multiplying by the length of the moment arm. Initially, the actuator is mounted from both sides to metallic plates onto the blocked force setup in open configuration. It is then heated to \( T > A_f \) for approximately 22 seconds to maintain the maximum torque. The same procedure is repeated for angles \( 0 \, ^\circ \leq \theta \leq 150 \, ^\circ \) with concurrent force and temperature measurement. Figure 5a shows the maximum torque measured at each angle. The maximum torque is measured as \( \tau_{\text{max}} = 34.1 \, \text{mNm} \) at angle \( \theta = 90 \, ^\circ \). Using the blocked torque measurement at this angle, \( E_A \) and \( C_A \) values are computed using (5) and (6), and included in Table II.

The experimental blocked torque for heating process at \( \theta = 90 \, ^\circ \) and the corresponding computed model is depicted in Figure 4b. The temperature of the actuator was limited to 82 \(^\circ\)C so that complete austenite phase is attained. The torque starts to gradually increase with the temperature increment until it settles at 34.1 mNm. Increase in phase transition
temperatures can be observed due to the stress induced by blocking or maximum loading condition. This phenomena of the SMA transformation temperature changing properties due to stress, is included as stress induced terms $\frac{C_2}{C_A}\tau$ and $\frac{C_2}{C_M}\tau$ in martensite fraction equations given in the previous section. For $M \rightarrow A$ the formulation in (3) yields $\tau = \tau_{max}(1-\xi)$ where $T$ in $\xi$ is taken as the actual measured temperature of the actuator at $\theta = 90^\circ$. Approximate values of $A_s = 50^\circ C$ and $A_f = 80^\circ C$ from the experiment are substituted into the model given in (3) and the maximum error is computed as 9.4 %.

C. Loading at constant rate for the martensite phase

In this test, mechanical properties ($E_M$ and $C_M$) of the actuator at room temperature ($\xi = 1$) are evaluated by loading at constant rate using the force measurement setup from the previous test. The procedure is as follows: one arm of the $\Omega$-SMA actuator is kept clamped to one of the metallic plates while the other arm is left free to slide along the other plate, but constrained in the perpendicular direction to the plate using a 3D printed clamp with clearance as a guideway. Its initial position is set to $\theta=135^\circ$, then the moving arm is rotated applying load towards $\theta=0^\circ$ at constant velocity, and the reaction force of the actuator is recorded as shown in Figure 5b. The maximum torque measures around 15.1 mNm at $\theta = 0^\circ$ which displays lower stiffness compared to those at complete austenite phase since $E_A > E_M$. Elastic modulus $E_M$ is determined using (5) where the linear region between $90^\circ \leq \theta \leq 135^\circ$ is considered and $C_M$ is computed by (6). The calculated parameters of the result are summarized in Table II.
Fig. 5. Blocked torque values measured for three actuator samples at different angles with 30° of interval (a) and the measured torque for loading at full martensite phase (b) for three actuator samples.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_s, M_f, A_s, A_f$</td>
<td>53.4, 37.8, 47, 67</td>
<td>°C</td>
</tr>
<tr>
<td>$E_A, E_M$</td>
<td>34.1, 19</td>
<td>GPa</td>
</tr>
<tr>
<td>$C_A, C_M$</td>
<td>1.11, 0.44</td>
<td>GPa°C</td>
</tr>
<tr>
<td>$\tau_{\text{max}}$</td>
<td>34.1</td>
<td>mNm</td>
</tr>
<tr>
<td>$P_{\text{max}}$</td>
<td>0.47</td>
<td>W</td>
</tr>
<tr>
<td>$\tau_{\text{max}}/\text{weight}$ [20]</td>
<td>486</td>
<td>mNm/g</td>
</tr>
</tbody>
</table>

V. MODULAR DESIGN FOR SELF-RECONFIGURABLE ROBOTIC ORIGAMI SURFACES

In order to demonstrate the actuator’s application in low-profile quasi-2D robots or Robogamis, we designed, fabricated and assembled multiple modules, each consisting of the following functional elements: the actuator, heater, curvature sensor and the triangular tile as depicted in Figure 6. A modular design approach for a robogami augments the simplicity of the design and assembly process with modifiable elements. Each tile, made of glass fiber, contains two extra pairs of holes for attaching other modules. Hence, besides being able to change each functional component, the proposed method allows us to achieve additional freedom by altering the surface size and consequently increasing or decreasing DoF by mounting additional modules or dismounting them by two pairs of M1 screws, respectively.

We adopt commercial strain gauges (RS Components Ltd) for curvature angle measurement as depicted in Figure 6. The sensor undergoes relatively high resistance changes for bending strains. Since the actuator has one-way deflection, the sensor layer here acts as a bias element to partially reverse the actuator motion while cooling. Thus, the sensor is sandwiched between 50 µm thickness kapton tapes in order to improve stiffness and also thermal insulation. Characterization test results provided in Figure 7 show approximately linear resistance change of the sensor for angular deflection of the actuator upon activation. Here, a similar experiment as with the load free test is carried out with the sensor mounted across the actuator hinge as shown in Figure 6 and characterized in a single direction from open to closed configurations. The deflection angle is captured using a video camera where the resistance value is measured using a digital multimeter (NI USB-4065, National Instruments) interfaced with LabVIEW software (National Instruments). It is worth mentioning that due to the elasticity of the sensor layer, it adheres to the curved shape of the actuator and heater hinge after multiple bending cycles as shown in Figure 6b. However, there is no contact between the sensor and heater layers; therefore, the heat effect on the strain sensor is minimal.

A. Controller design

There are generally two control goals for SMA actuators: position and force. Control parameters can be resistance, temperature, position or force feedback. Our application focuses on the robogami system with multiple creases that can self-fold into different 3D shapes. Therefore, accurate position control of the actuators is essential to achieve the versatile shapes. We present here angular position control of the Ω-SMA torsional actuator by PWM duty modulation of power input. Since we are only interested in accurate positioning of the actuator, we designed our controller based on angle feedback from the
bending strain sensors described earlier. Different from our previous work on an on-off controller of SMA actuators [18], here a PI controller is adopted to achieve desired positions for each actuator.

The controller design is as follows: if a closing hinge with a measurable bending angle \( \theta \) is considered, then the control goal within PI controller framework can be written as

\[
D = K_p(\theta_{set} - \theta) + K_i \int (\theta_{set} - \theta)
\]

(7)

where \( D \) is the PWM duty value of the power supplied to the heater, \( K_p, K_i \) are the proportional and integral gain constants to minimize the error in bending angle which is the difference between the set angle \( \theta_{set} \) and the measured angle \( \theta \) coming from the strain sensor. In order to avoid over-heating of the actuator, we introduced limiting functions for the controller duty value output as

\[
D = \begin{cases} 
D_{lim} & \text{if } D > D_{lim} \\
0 & \text{if } D < 0
\end{cases}
\]

where the limiting duty value is a positive real number between \( 0 \leq D_{lim} \leq 1 \).

\[ \Delta R = -0.0053 \theta + 0.83 \]

Fig. 7. Curvature sensor resistance change for angular deflection of the actuator upon activation. The sensor displays minimal effect of the heat dissipating from the micro-heater layer.

\[ \Delta R = \frac{\theta - 90}{0.42} \]

Fig. 8. Experimental setup for self-reconfigurable robogami surface. S1, S2 and S3 denote the transistor switches for regulating DC power flow to modules M1, M2 and M3 with PWM signals. Multiplexer MUX is employed for buffering three strain gauge resistance signals R1, R2 and R3 and sending to the digital multimeter through single channel. The signals are parsed, processed and then fed to the microcontroller circuit by means of data acquisition board DAQ as analog voltages V1, V2 and V3.

B. Implementation and Results

In order to evaluate the effectiveness of the method, the setup given in Figure 8 is employed to test a robogami surface with four tiles, illustrated in Figure 9. It consists of three actuated modules to demonstrate the capability of constructing various shapes in 3D space by the selective activation of three actuators and controlling the folding angles. The setup is as follows: three independent PWM duty control outputs from the microcontroller are supplied to control the switches S1, S2 and S3, hence regulating the power flow to the heaters at modules M1, M2 and M3. The resistance changes in the strain sensors R1, R2 and R3 are acquired by the digital multimeter. We overcome the limited number of channels available on the digital multimeter by including a multiplexer (MUX) for buffering and feeding data through a single channel to the digital multimeter communicating with the LabVIEW interface. The resistance data is extracted in LabVIEW then converted to angles using the characterization plots given in Figure 7. Then these angle values are further represented as analog voltages V1, V2 and V3 and sent to the microcontroller through a data acquisition board (DAQ USB-6008, National Instruments) closing the loop. In this arrangement, we take advantage of using a single power supply and handling multiple control and feedback signals independently.

The angle control response of each actuator at three modules along with the reference angle is shown in Figure 9. The system is initially at rest then \( \theta_{set} = 90^\circ \) is set as reference to actuators 1 and 3 while no reference is given to the actuator 2. Then a reference of \( \theta_{set} = 110^\circ \) is given to all three actuators in order to form shape 3; the tetrahedron. Some variation in the actuator angles is due to minimization of the error when the set point is attained. Here, the duty cycle becomes close to zero, thus the heater becomes inactive for short time, the actuator cools down at that moment decaying from the reference angle until it is activated again to attain the set point.

VI. CONCLUSION

A lightweight low-profile Ω-SMA torsional actuator is presented in this paper. This customizable actuator consumes a maximum of 0.47 W of power and can produce torques of 34.1 mNm, with a torque-to-weight ratio of 486 mNm/g. One dimensional constitutive model of the actuator was derived based on its mechanics and adopting the Liang-Rogers thermomechanical model for SMAs. This analytic model is supported by characterization experiments in three loading conditions; unloaded, loaded and blocked. The actuator parameters could be determined from these characterization tests. Our studies demonstrated that the mathematical model closely complies with the characterization experimental results with 11.3 % and 9.4 % deviation for load-free and blocked-load, respectively. Moreover, position control of the actuator is achieved by integrating a curvature strain sensor. The proposed actuator-heater-sensor-tile modules were implemented into a multi-DoF Robogami. We demonstrated with experimental results from this prototype that it is possible to obtain desired shapes accurately with closed-loop control of the actuators. From the
comprehensive performance tests we have modeled and exhibited functional applicability and possibly attain the maximum physical and material limits of SMA torsional actuators.

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