High-Displacement, Fiber-Reinforced Shape Memory Alloy Soft Actuator with Integrated Sensors and Its Equivalent Network Model

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For soft robotics, shape memory alloy (SMA)-based elastomeric actuators are a promising material combination but their maximum stroke is limited by the small inherent contraction of SMAs. In this work, a textile-reinforced soft actuator is presented, which has additional SMA wire length included in the textile structure as well as a sensoric textile to track the actuator’s pose. This strategy eliminates the need for external SMA wires with extra mechanical components. Various experiments with different excitation voltages are performed to show the actuator’s performance. In a horizontal setup, the soft actuator reaches a bending angle of 270° at a power input of 18 W. The integrated sensor reflects the actuator’s position but is also influenced by the temperature increase during activation. Moreover, an equivalent circuit model is proposed that includes the actuator, sensor, and mechanical support structure in one model. The model incorporates not only the mechanical but also the thermal and electrical domains. The simulation results are in good agreement with the experimental results.

1. Introduction

For several years, soft robotics has been an emerging field of research. As opposed to traditional rigid robots, this new class of robots offers higher versatility, adaptability, and resilience. Furthermore, they have great potential for human–machine interaction, robotic surgery, or the exploration of irregular environments. The bases for the new generation of robotics are novel materials that are highly deformable and resilient and couple actuation and sensing. A potentially well-suited type of material is the class of fiber-reinforced elastomer composites. With their anisotropic fiber reinforcement and soft matrix material, they are similar to biological role models composed of tendons, ligaments, and soft tissue. In addition, active and sensory materials can be integrated into the reinforcing textile, equivalent to muscle and nerve fibers in biological structures.

Elastomeric materials possess the ductility (>100%) and low modulus (<1 MPa) of soft tissue. If reinforced with fibers or textiles, the resulting composites’ mechanical properties can be tailored to the specific application and can combine high flexibility with high resilience. However, to be able to interact with their environment or operate in closed-loop control, sensors have to be integrated as well.

A powerful actuator type is shape memory alloys (SMAs) such as nickel–titanium (Ni–Ti) alloy. They can be activated electrically by Joule heating and have enormous energy density ($10^7$ J m$^{-3}$) and power per mass (50 kW kg$^{-1}$). One major disadvantage of SMAs is the low maximum strain of 4–8%, especially if more than $10^5$ working cycles are desired. This limits the potential of SMAs in biomimetic structures as biological muscles’ maximum strain of 20% far exceeds that of SMAs. Other actuator types such as twisted coiled polymeric actuators, dielectric elastomer actuators, and ionic polymer–metal composites offer similar or higher strains than biological muscle but are limited in their force output.

Despite their limited maximum strain and strain rate, SMAs have been implemented in various soft robotic systems, such as an octopus arm, a caterpillar robot, and active hinges. Still, the low maximum strain poses a problem. Lee et al. proposed a solution using additional SMA length outside the structure, which indeed increased the maximum deflection of a bending beam. The contraction of the SMA under heating produced significant out-of-plane deflection with a bending angle of 270° for untapered beams and up to 400° for tapered beams. However, the positioning of the SMA wires outside the structure leads to increased space requirements and bulkier setups.

In Lee’s work, as in most SMA-based active structures, the extrinsic one-way effect is used. The prestrained SMA contracts upon heating over the transition temperature and deforms the passive structure around it, which acts like a spring, as shown in Figure 1a. When cooled, the spring or passive structure resets the SMA wire to its original length.

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Another important aspect in actuation technology and soft robotics is the determination of the effector pose, meaning the current deflection of the structure.\cite{16} SMAs can be used to monitor their contraction by measuring their electrical resistance.

During the transition between the martensitic and austenitic phase, the electrical resistivity is a good indicator for the strain because the phase transformation dominates the resistance change.\cite{17} With increasing contraction the resistivity decreases, but outside of the phase transition Ni–Ti, like most metals, has a positive temperature coefficient. Therefore, the strain–temperature–resistance behavior is nonmonotonic around the start and finish of the phase transition, which severely complicates its use as a strain sensor (Figure 1b). Thus, additional integrated sensors are necessary to allow autonomous operation in closed-loop control.

Moreover, to better understand the complex interaction between the actuators, sensors, and passive structure suitable models are needed. Currently, there are approaches to model the behavior of SMA materials, especially the hysteresis of the strain–stress–temperature relation.\cite{18} These models can help to achieve a better understanding of SMAs but are difficult to transfer to real structures.\cite{19} Other approaches include real-time finite element modeling to control soft robotic structures of fluidic actuated structures but do not consider sensory elements and are only used for open-loop control.\cite{20} Most publications regarding the integration of additional sensors in soft robotic structures perform calibration cycles to calibrate the sensor signal with the excitation variable without considering the actuator behavior or predicting the sensor response.\cite{21} Overall, there is a lack of approaches that include structure, actuators, and sensors in one model. These challenges of high-strain actuation, integrated sensors, and their modeling are addressed by this work (Figure 1c).

In this article an SMA-actuated bending beam is presented with a textile-integrated additional SMA wire length to compensate for the low maximum strain. The achieved deflections were large and comparable to other setups in literature but without the added space requirement and bulkiness of outside SMA wires. Furthermore, silver-plated sensor yarns were included to monitor the deflection. Two sensor yarns were included: one in a straight configuration and one ondulated. In theory, the ondulated yarn should be strained significantly less than the straightened sensor yarn and could be used to compensate the temperature sensitivity of the silver-plated yarn.

The setup was characterized under cyclic excitation by Joule heating while tracking the movement optically with a camera. In addition, the soft actuator was modeled as an equivalent circuit model (ECM) that incorporates transducers between the mechanical, electrical, and thermal domain to emulate the behavior of the actuator–sensor setup. Finally, the results of the ECM simulations and the experimentally obtained data were compared and analyzed. The bending beam can potentially be used in a soft gripper, for locomotion in uneven terrain, or in other applications of soft robotic systems.

2. Results

2.1. Manufacturing

For the characterization of the system, several samples of the active bending beam were manufactured. Ideally, the reinforcement textile has low bending stiffness but high tensile stiffness and good adhesion to the elastomer, which was achieved by using thin glass-fiber fabric. The tailored fiber placement (TFP) of the SMA hybrid yarn (SMA-HY) leads to a straight configuration of the actuator wire over the beam length with two additional loops that add a supplementary wire length to boost the deformation potential (Figure 2a). Although the TFP process damages the reinforcement textile in the loop area, this did not affect the bending beam’s performance because the affected area was small and supported by the loop geometry.

Important material parameters for the sensor textile are low stiffness, high stretchability, a high gauge factor, as well as a linear strain resistance response. The sensoric textile consisted of three components: base textile, straight sensor, and ondulated sensor (Figure 2b). The base textile was a highly stretchable polyester knit on which the sensor yarns were embroidered. During infiltration with silicone rubber, both textiles were separated by a 3D-printed mold with the outer edges glued to the mold to prevent distortion of the textile and ensure the targeted layer sequence (Figure 2c), especially under vacuum. When the
samples are molded at room temperature and under vacuum, the silicone rubber’s low viscosity leads to a well-infiltrated reinforce-
ment textile with good adhesion between both and only a mini-
mal amount of air bubbles.

2.2. Deformation and Sensor Signal Under Activation

The resulting bending beam showed a large amount of deforma-
tion when actuated with sufficient power. The minimal voltage
that resulted in movement of the bending beam was 9 V, which at
a resistance of 8 Ohm equals a power input of 10.1 W. It is impor-
tant to note that all experiments were conducted at room temper-

ture of 22 °C without forced convection. Full deformation was
reached with an activation voltage of 12 V and a power of 18 W,
respectively, and amounts to a bending angle of 270° in a hori-

tzontal setup (Figure 2d). This is equal to the maximum deforma-

tion reported in the literature for untapered beams with the same

hight but with additional external wire length of 300 mm that is
not needed in the presented setup. Because the optical markers
lead to collisions with the mounting, the characterization experi-

ments were performed in a vertical configuration where gravity
strongly counteracts the beam’s motion.

In Figure 3a, the bending beam with the optical markers
attached to it is shown before and during activation. The bending
beam was already slightly bent at the beginning due to the insuf-
ficient retraction after it was activated for the first time.
Consequently, all specimens were actuated repeatedly to maxi-
mum deformation before the characterization experiments were
conducted. Thereafter, the remaining out-of-plane deformation
was considered as the initial state with a 0° bending angle.

The optical markers provided a reliable means of tracking the
beam’s motion and bending angle over its length. For the
activation with 12 V, the tracked positions and resulting beam
conformation are shown in Figure 3b. To evaluate the beam’s
motion, the angle between the last and penultimate sections
was taken as a metric, which underestimated the true bending
angle at the tip of the beam but was better suited for comparison
with the developed ECM.

In Figure 3c, the bending angle over a cyclic activation with
varying voltages is shown. Each cycle consisted of a heating phase
of 3 s and a subsequent cooling cycle of 10 s. For the activation
voltages of 9, 10, and 11 V the bending angle is comparably low,
which is due to the hysteretic, nonlinear behavior of the SMA and
consequently a low resulting deformation for temperatures at the
beginning of the phase transition. When activating the bending
beam with 12 V, the maximum bending angle of the first cycle is
10° and increases to 25° for the tenth cycle because the heat intro-
duced during each activation period is not dissipated fully during
the following cooling period. This leads to the increasing deforma-
tion with increasing cycle number. For the activation with
13 V this effect increases up to a maximum bending angle of
58° in cycle 7. After reaching this maximum bending angle, it
does not increase further over the next three cycles because
the phase transition is completed. When the maximum bending
angle is reached, slight torsional motion overlays the bending
motion. However, this is ignored for the evaluation and only
the bending motion is considered.

The resistance signal of the integrated sensor yarns
(Figure 3d) generally followed the bending angle of the soft actu-
at or well, for both 12 and 13 V activation. However, the relative
resistance change was relatively low even for large deformation.
This is due to two factors: First, the theoretical strain that was
applied to the sensor textile at the maximum bending angle of
58° was only 2.4%. For a gauge factor of 2, which is standard
for metallic strain gauges, this would amount to a relative resistance change of 4.8%. The second factor leading to the low resistance change was the nonlinear strain–resistance relation of the sensor yarn material. Because it was a plied yarn, an applied strain led to structural deformation at first. Before the material itself was deformed, the individual filaments straightened and aligned in a first step. Consequently, the resistance change was nearly zero for this structural deformation. When tracking the resistance change of the pure yarn during a tensile test, the relative resistance change at an elongation of 2.4% was only 1.1% (Figure S1a, Supporting Information). When considering both factors, the resistance signal may be a good indicator for the beam’s pose.

Another influencing factor of the resistance signal was temperature, with the sensor yarn having a positive temperature coefficient of 2.9 \times 10^{-4} \text{ K}^{-1}. Although most of the heat was dissipated on the side where the SMA-HY was closer to the surface, over time the whole beam heated up, resulting in an increase in resistance.

The ondulated sensor yarn, which was supposed to be more sensitive to temperature than to strain of the sensor textile, did not show any correlation between the sensor signal and temperature or strain either over several samples or between different activation cycles. This might be due to local slippage or reorientation of the sensor yarn in the matrix resulting in local stress and strain peaks. For that reason, the ondulated sensor yarn’s signal was not useful as a means to compensate for the temperature’s disturbing influence on the straight sensor yarn. The same mechanism could also cause the smaller peaks between cycles seven and eight.

2.3. Simulation by an ECM

The next subsection describes the modeling of the soft actuator as an equivalent network model (see Figure 4a). In contrast to other models reported in the literature, the ECM considers not only the mechanical structure, but also the thermal and electrical behavior of the actuator and sensors. Therefore, electromechanical analogies were used that enable the description of mechanical structures and their coupling to the thermal and electrical domain by electrical components and circuits.[22]

The activation of the whole system was accomplished by a voltage source, which led to a current flow through the SMA wire represented as a resistor. It was assumed that the electrical power input to the system is completely converted to thermal energy by Joule heating. The introduced heat flux was represented by a current (i.e., heat flow) source. Both the SMA-HY and the rest of the bending beam were considered as lumped parameter models in the thermal domain. The thermal domain incorporated two capacitors equivalent to the heat capacities of the SMA-HY and the matrix material. Three resistors represented the thermal conductivities inside the beam and controlled the heat transfer to the environment.

In this model the SMA acted as a transducer between the thermal and rotational domains because the temperature difference leads to a contraction of the SMA wire and, thus, a moment acting on the bending beam. The mechanical structure of the soft actuator was divided into the rotational domain with electrical inductances equating the rotational springs with their bending stiffness. In the translational domain the mass of the beam sections was represented with the beam being segmented into four sections.
sections. Finally, the sensor circuit consisted of a constant current source as in usual multimeters and a variable resistor representing the sensor yarn. The variable resistor responded to the angular position of the beam as well as the temperature on the lower side of the beam where the sensor textile was located. Both influencing factors were considered as linear functions.

Figure 4b,c shows the simulation results for an activation voltage of 13 V with a heating time of 3 s and a cooling time of 10 s identical to the experimental parameters. As expected, the cooling process was much slower than the heating process.

In general, the simulation and experimental results were in good agreement considering the simplifications made during abstraction. A first difference to note is that the simulated bending angle was not cut off at 58° but rose further to 63°. This is because the thermomechanical transducer in the ECM had a constant coupling factor and therefore could not emulate the phase transition’s end. In contrast, the actual bending beam stopped moving at the end of the SMA’s phase transition. At that point, the beam’s stiffness and the resulting force as well as the force applied by the SMA reached an equilibrium.

In addition, the model overestimated the deformation and the resistance response during the first cycles. The heat capacity calculated from supplier datasheets based on the geometry was apparently lower than the actual heat capacity. Therefore, the temperature rose slower in reality than in the simulated system. For the last three cycles, the experimentally obtained values were in good agreement with the simulation results. At this stage, the system reached a steady state when the same energy introduced in the heating cycle was dissipated in the cooling period. The same behavior was observed in the ECM simulations. Therefore, the modeling approach and the developed model are a promising option but still require optimization. Especially, for changing heating and cooling regimes, which would appear in real-world applications, the model should be improved further.

3. Conclusion

One disadvantage of soft SMA-actuated systems is the low maximum contraction and, therefore, the limited maximum stroke of
these soft actuators. Previous attempts to overcome this limitation require additional external SMA wire length, which leads to more bulky, exterior systems with pulleys. Thus, the advantage of integrated actuators, that is, the need for additional mechanical parts, is eliminated. In this work, a textile-reinforced SMA-based soft actuator was presented that achieved a bending angle of 270°, previously only possible with an additional external wire length. By adding loops of an SMA-HY, in which the SMA can slide freely within the matrix, the maximum achievable deformation is decoupled from the length of the passive structure.

Moreover, a textile equipped with sensor yarns was integrated in the soft actuator, which allows tracking of the deformation behavior of the active beam. However, the signal was nonlinear and cross-influenced by the temperature increase due to the Joule heating of the SMAs. The deformation behavior and resistance response were simulated with an ECM that incorporated not only the mechanical structure but also the thermal and electrical domains. Overall, simulation results were in good agreement with the experimental results, considering the simplifications made in the modeling process. The limitations include the assumption of a lumped parameter system in the thermal and electrical domains as well as linear stress–strain, resistance–strain, and resistance–temperature relations. It would be interesting to use the developed modeling methodology to predict the soft actuators’ behavior and, thus, improve control algorithms or use it to achieve more accurate self-sensing.

The proposed design overcomes previous limitations of SMA-based soft actuators, making them a feasible option for soft robots or other soft mechanisms. Further improvements can be made with respect to elimination of the temperature influence on the sensor’s strain response. In addition, modifications to the matrix system, the geometry of the textile structure, with advanced integration techniques can expand the motion range of the beam, lead to more complex motions, or improve the generated force. Finally, the developed approach should be integrated in more complex systems to perform tasks such as locomotion and gripping.

4. Experimental Section

Materials and Manufacturing: The base textile material used in the experiments was a glass-fiber 2 × 2 twill weave. It had a thickness of 0.27 mm and the actuators were attached via TFP. To ensure adequate adhesion of the SMA (Alloy H ox. Sa, Merny GmbH, Germany) to the composite and mobility of the SMA in the structure a core–sheath configuration was used. The SMA was incorporated in a hybrid yarn structure with a sheath of a 320 tex glass roving and polypropylene fibers as presented by Ashir et al.[23] To integrate the SMA-HY an embroidery machine (type SCY 0200-650D by ZSK Stickmaschinen GmbH, Germany) was used with a 27 tex polyester yarn. To surpass the limited contraction of the SMAs, two loops—one at the beginning and one at the end of the bending beam—were formed. The loops added an additional SMA length of 40 mm to the two wires of 200 mm length.

The sensor textile was a circular knit made from polyester with the embedded sensor yarn. As the sensor yarn, a silver-plated polamide yarn (Shieldex 110/34, Statex Produktions & Vertriebs GmbH, Germany) was used (see Figure S1, Supporting Information). During the embroidery process, the yarn was used as a lower thread with higher tension than the upper thread to promote straight alignment, and thus a better sensor response. The sensor yarn’s electromechanical behavior was evaluated using a zwickLine Z2.5 tensile testing machine (ZwickRoell GmbH & Co KG, Germany) with a 100 N load cell. The coupled resistance measurements were conducted using a Fluke 8846A multimeter in a four-wire setup at a frequency of 2 Hz.

For the molding process, the textiles were glued to both sides of a 3D-printed mold to prevent in-plane or out-of-plane distortion. After that, the mold was placed on an aluminum plate and polydimethylsiloxane (Sylgard 184, Dow Corning, USA) was mixed, degassed, and poured slowly onto the reinforcement textile. When the mixture had flown through the textile, the step was repeated several times until the mold was completely filled. To evacuate the remaining air bubbles, the mold was put in a vacuum oven for 1 h. Afterward the specimens were cured at 45 °C for 12 h. Once the silicone rubber was fully cured, a scalpel was used to cut the specimens out of the molding frame.

The specimens were then clamped between two metal sheets of 25 mm length, leading to a remaining free length of 195 mm. The width and height of the specimens were 30 and 3 mm, respectively. After the specimens were securely clamped, the SMA wires were straightened, fixed, and contacted in a luster terminal.

Electromechanical Characterization: Evaluate the active beam’s behavior under excitation by Joule heating, a test bench with a power supply, digital multimeter, and camera was used. The SMA wires were activated with a programmable power supply (R&S HMP4040 Four-Channel Power Supply, Rohde & Schwarz, Germany). Each cycle lasted 13 s with 3 s activation time and 10 s to cool down the SMAs. Tracking the sensor yarns’ resistances was achieved using a Keithley multimeter (Keithley DAQ6510-7700, Keithley Instruments, USA) in a four-wire setup to minimize the influence of wiring and contacting. The excitation voltage was varied between 8 and 13 V. Between each experiment, the sample was left without activation for at least 5 min to cool down to room temperature.

The beam’s position and conformation during activation were tracked by a camera (GoPro Hero3+, GoPro, USA) at a frame rate of 120 Hz with a resolution of 1280 × 720 pixels. The fish-eye distortion of the camera was corrected by calibrating with a checkerboard image and undistorting the images afterward using Matlab (MathWorks Inc., Natick, USA). Four equally spaced markers with small checkerboards were glued on the specimens to precisely track the beam’s conformation. The image analysis was performed automatically by algorithms coded in Matlab.

Parameter Determination of the ECM: The parameters of the circuit elements were calculated from the manufactured geometry, experimental results, and supplier information. For the polydimethylsiloxane, the thermal and mechanical properties supplied by Dow Corning were used. From these the inductances were calculated as the inverse rotational stiffness or bending admittance. The inductance of one section of the bending beam was then 1.86 × 10⁸ H.

Similarly, the mass of the beam sections was calculated by weighing the beam and assuming uniform mass distribution over the beam’s length. This led to capacity of 6.2 × 10⁻⁹ F for each beam section.

The silver-plated yarn’s strain–resistance behavior was characterized by tensile tests with simultaneous resistance measurements. Its temperature coefficient was calculated from measuring the resistance in a four-wire setup while heating the yarn on a hot plate between room temperature and 100 °C. The resulting temperature coefficient was 2.9 × 10⁻⁴ K⁻¹.

The maximum force that was applied by one SMA was 20 N on average. The voltage at the end of the beam in the rotational domain was equivalent to the angular velocity and was thus integrated over time to calculate the angular position. All simulations were performed with LTSpice XVII (Analog Devices, Norwood, USA).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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The authors declare no conflict of interest.

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Research data are not shared.

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