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Highly Deformable 3-D Printed Soft Robot Generating Inching and Crawling Locomotions with Variable Friction Legs

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***Abstract*— Soft and continuum robots have the useful capability of adopting intricate postures and conforming to complex shapes. Furthermore, structures built from soft materials propagate mechanical energy from one part of the body to another, depending on its body shape, boundary condition, stiffness distribution, and so on. This makes the robots capable of producing a large number of force profiles to achieve useful behaviors and functionalities, even using a small number of actuators. Exploiting the soft mechanical property also enables to generate functional frictional forces, which is a key issue in controlling robot locomotion. In this paper, a highly deformable 3-D printed soft robot (PS robot) is presented, which is capable of generating complex, robust gaits on different inclines using a novel variable friction leg design. This design changes the frictional force depending on the robot posture and shape to facilitate robot locomotion. Shape memory alloy (SMA) coils are embedded into the robot in such a way that they act both as structural elements and actuators. This is the first soft robot platform produced by 3-D printing making fabrication simple and fast.**

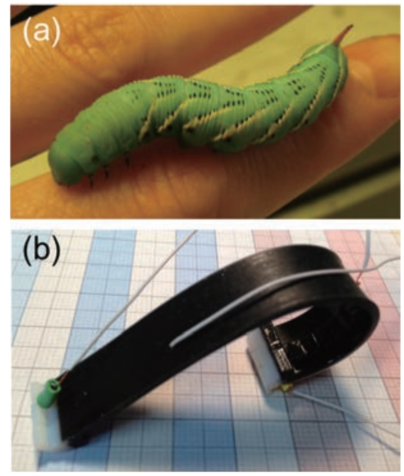

Fig. 1. (a) Model animal of soft robot, *Manduca sexta* and (b) Printed Soft robot (PS robot) proposed.

I. INTRODUCTION

Animals are largely composed of soft materials such as muscles, tendons, and several layers of skin-like tissues, which enables to interact with their uncertain environments actively, leading to adaptive and robust behaviors against dynamically changing environment (e.g., locomotions of caterpillars and worms, manipulation of octopus arm and elephant trunk). Inspired by this, soft robotics recently has attracted a lot of attention for many roboticists [1], [2], [3], [4], [5]. The design concept of soft robotics is not only to use soft, deformable, and continuum materials into robot bodies but also to implement morphological computation [6] or active sensing [7] exploiting the deformability and non-linearity of the soft body so as to overcome the limitations of traditional hard and rigid robotic systems.

The challenge, however, remains to design and actuate the soft body effectively. In particular, the main issues are how to control the frictional forces and body shape to achieve desired behaviors and functionalities (e.g., locomotion). To obtain complex and robust directed movements, there are two major design strategies. The first strategy involves having simple plant dynamics. In this case, a complex input (actuation) produces complex outputs (locomotion gaits). The other strategy involves having a complex plant which, given simple inputs, generates complex outputs. The latter strategy is analogous to morphological computation and is widely prevalent in nature, e.g., motor system control at the level of tissues and molecular mechanisms of state changes [8].

In this research, we explore the concept of morphological computation by exploiting the intrinsic non-linear, viscoelastic, and continuum response of a soft robot. Unlike rigid robots, the actuators can be distributed throughout the structure giving them both actuator and structural functionality [5]. The continuum nature of soft robots also makes it possible to create a large number of force profiles even using a small number of actuators, which can then generate different gaits. Furthermore, soft materials can be exploited to strategically generate frictional force for locomotion. This is because the deformation capability of soft robots allows it to vary the amount of contact surface with the environment, resulting in dynamically-shape-dependent frictional force on the robot. This is in sharp contrast to rigid-body robots that tend to have a limited number of contact points. This intrinsic potential of soft robots to vary frictional forces makes them interesting candidates for variable terrain vehicles.

The paper presents a 3-D printed soft robot (PS robot) inspired by highly deformable, relatively simple-shape animal, i.e., caterpillars (*Manduca Sexta*). Key aspects for designing

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the soft robot are as follows: 1) a posture-dependent change in contact friction created by both structural and material design considerations; 2) coupling the mechanical action of actuators through the deformable chassis and; 3) exploiting the dynamic responses (e.g., viscoelastic and continuum properties) of soft materials. The experimental results shows that exploiting complex mechanical dynamics of soft materials allows simple control to promote adaptive and versatile behaviors. The results can contribute to an understanding of how a living system generates versatile and adaptive behaviors with morphological computation of their bodies.

II. Soft robot design

The printed soft robot (PS robot) is presented in Figure 2, which cosisting of a soft body with variable friction legs and two coiled shape memory alloys (SMAs). The body is printed using multi-material printable 3-D printer (Objet Connex 500™ 3-D printer) with two materials. One is soft rubber-like Objet TangoBlackPlus™. Another is hard polypropylene-like Objet VeroWhitePlus™ [9][1]. The structure with blocks aligned in a straight line on the ventral side (see Figures 2(e)) has holes along the straight line to guide SMA coil inside and allows the SMA coil to cool quickly. The SMA coils (BMX75, Toki Corporation)[2] are electrically actuated, and are tactfully embedded in the structures on the soft robot surface. In particular, as shown in Figure 2(c), the SMA coils were arranged side-by-side and overlapped in such a manner that distal attachment points are at each end of the robot [3]. This mechanical design allows for them to act as an actuator and a key structural component to send bending wave from one part to another (e.g., from SMA2 part to SMA1 part).

A. *Variable friction legs*

Rigid body roboticists use different mechanisms for locomotion over variable terrains, e.g. hybrid leg-wheel robots [10], passively compliant axles [11], etc. A novel design concept is proposed in the given section that may be applicable to soft caterpillar-like robots for locomotion purpose. The proposed design, as shown in Figure 3, uses two materials: TangoBlackPlus™ (black color substance) and VeroWhitePlus™ (white color substance). The TangoBlackPlus™ has higher friction coefficient than VeroWhitePlus™.

Use of materials with two different friction coefficients allows the robot to switch friction with the ground on an edge of the robot by bending the body (see Figure 3(b)). By deforming the body appropriately, this friction switch mechanism allows the robot to generate frictional force for locomotion purpose (the detail will be explained in the next subsection). The proposed macro-scale concept is in contrast to micro-scale directional friction, chemical adhesion or gripping mechanisms as seen in nature [12]. With the knowledge of difference in friction coefficients of the two materials, it is hypothesized that such (or similar) variable friction leg design will allow soft robots to maneuver variable friction terrain.

The design of the current leg allows the robot to vary frictional force with regard to the tilt angle (Ψ), as can be seen in Figure 4. The figure shows the variation of frictional force on the robot leg as a function of tilt angle (Ψ). Here μ_{TB+}, μ_{VW+} indicate the static friction coefficients of the two materials. The tilt angle is proportional to the radius of curvature of the robot (i.e. the robot shape) when the soft

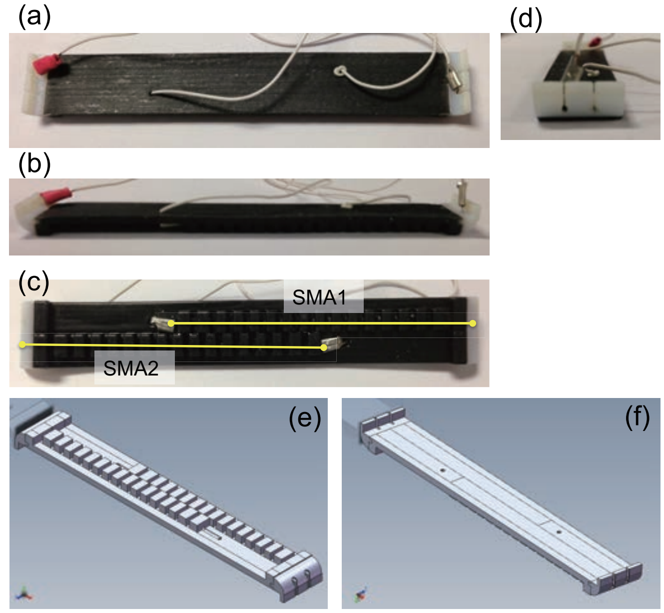

Fig. 2. (a) Top view of the robot. (b) Side view of the robot. (c) Bottom view and arrangement of the SMAs inside robot body. The SMAs are embedded overlapped along the body axis, which fulfills the dual actuator-structure functionality. (d) Side view of the robot from the head/tail. (e) Bird's eye view of the cad data (the ventral side is top). (f) Bird's eye view of the cad data (the dorsal side it top).

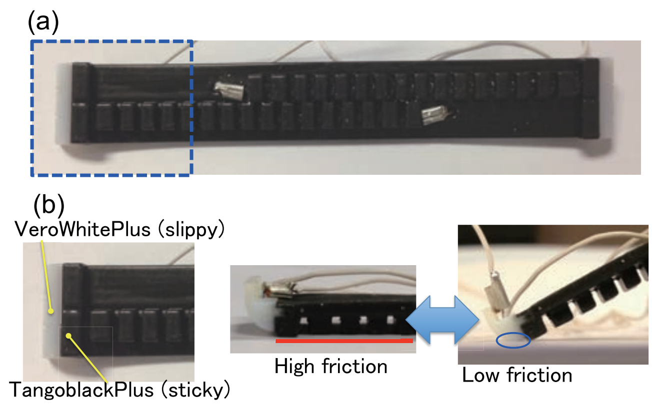

Fig. 3. Variable friction leg design. Red line indicates high friction surface with TangoBlackPlus and blue ellipse indicates low friction contact point with VeloWhitePlus.

[1]The mechanical properties of the materials are found in the following url: http://www.stratasys.com.

[2]The detail information of the SMA coils is found in the following url: http://www.toki.co.jp/biometal/english/contents.php.

[3]Each end of each SMA are connected with electric cable with a crimping terminal.

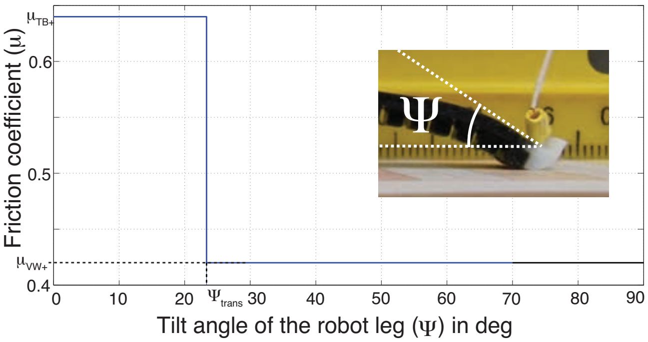

Fig. 4. Variation of friction coefficient with regard to tilt angle Ψ. The friction coefficients of TangoBlackPlus^{TM}, VeroWhitePlus^{TM} are denoted by μ_{TB+}, μ_{VW+}, respectively. Ψ_{trans} denotes the transition tilt angle when the friction change occurs.

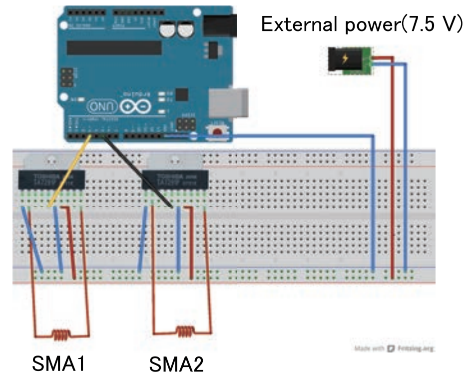

Fig. 5. Circuit board consisting of Arduino Uno and two motor drivers as control system for the soft robot.

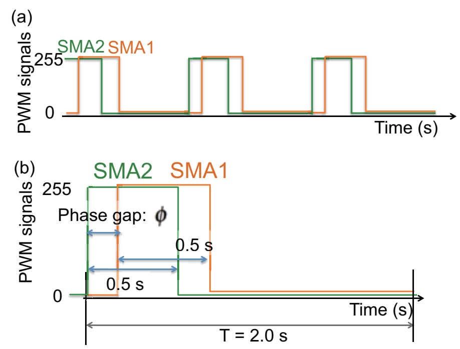

Fig. 6. (a) PWM signals generated by the microcomputer, and (b) one period of the signal. The time period T is fixed at 2 s, and the actuation time is fixed 0.5 s. The phase gap ϕ denotes the difference in time between actuation of two SMA coils. Here, SMA1 and SMA2 denote the SMA coils described earlier in Figure 2.

robot is modeled as a constant curvature continuum robot [13].

B. Gait Generation

A wave is an ubiquitous phenomenon (e.g., vibrational, trembling motion) in elastic, deformable, and continuum bodies. In this soft caterpillar-like robot, it is initiated by an actuator (e.g., contracting of SMA1) and deforms the body part around the SMA. The elasticity of the body transfers this force from one part of the body to another. Hence, by exploiting this body property of the soft robot, SMA1 and SMA2 are capable of generating waves at different frequencies, amplitude, phase differences, and wavelength (depending on the actuator arrangement on the body). The propagation of the wave through the body depends on the material properties, e.g., viscoelasticity, friction generated on the body. Our hypothesis is that interfacing these waves through body dynamics of soft robots allows the robot to generate multiple locomotion gaits (e.g., inching and crawling motions as can be seen in real caterpillars) with a fewer number of actuators (two in this case).

From the kinematics point of view, both inching and crawling motions of real caterpillars are generated by producing retrograde waves. Bending/contracting wave starts from the rear part and moves forward along the body. Inching gait is a modal wave with its wavelength almost equal to the body length, whereas crawling gait is a modal wave with its wavelength approximately half of the body length or less than that. Based on this biological finding and our mechanical design in Figure 2, we focus on time difference of firings between the two SMAs (i.e., phase gap ϕ) so as to reproduce the caterpillar locomotion gaits. Of course, the other variables are available for designing the actuation signals such as amplitude of the SMA actuators (voltage applied across the SMA), frequency of actuation of SMA, and wavelength of SMA actuation signal (decided by SMA coil arrangement). However, as a preliminary experiment, phase gap ϕ between the SMA actuation is varied and the rest variables are fixed.

In order to realize such control system and to confirm our hypothesis, we built open loop control for the robot. The circuit board consists of one Arduino Uno (Arduino, 2012) and two motor drivers (TA7291P, Toshiba Co.) as shown in Figure 7(a). The Arduino Uno was programed to generate PWM signals as input signals to each motor drivers. Each motor driver switches on and off external power supply (7.5 V) to each SMA embedded in the robot. The time period of the SMA actuation signal is set to 2 s [4], the phase gap ϕ is varied between 0.1 s to 1.0 s.

III. Experiment

A. Experimental setup

To evaluate the validity of this PS robot, we conducted the following two experiment: (i) measuring distance traveled on flat ground and observation of the locomotion gait when changing phase gap ϕ, and (iii) measuring distance traveled when surface friction conduction varies. In these experiments, distance traveled of the robot for 10 s is observed. The robot was programed to generate locomotion for 10 s

[4]Although the SMA coils have muscle-like properties, they do have limitations as robotic actuators: their maximum actuation frequency is limited by their cooling time. Due to this, we set one cycle time as 2 s for cooling SMAs, which seems to be sufficiently long, as we look the motion (see the attached movie) and standard deviations in Figure 11.

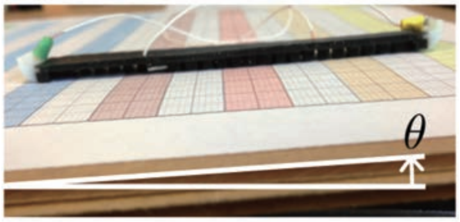

Fig. 7. Photograph of experimental setup. The robot is on an incline of angle θ.

and rest for 2 s. This process was repeatedly conducted for 5 times. The experiment was conducted in room temperature.

1) Observation of the locomotion gait: To observe the locomotion gait of the robot, we recorded the motion from side of the robot during locomotion. From the movie, we made the snapshots. Since the body part constructed with TangoBlackPlus can be anchoring surface when the part touches the ground, we marked with red line on the surface.

2) Locomotion on variable surface friction conditions: It is desired to observe robustness of the locomotion gaits when changing surface friction condition. The static friction coefficients of the two materials with the experimental surface are $\mu_{VW+} = 0.42$ and $\mu_{TB+} = 0.64$. To vary the surface friction condition, the soft robot is operated on an incline with angle θ as indicated in Figure 7. The effective friction (μ_{eff}) can be calculated as

$$\mu_{eff} = \mu - \tan\theta, \tag{1}$$

where $\mu = \mu_{VW+}, \mu_{TB+}$. The angle θ is positive when the robot is locomoting down the incline and negative when attempting locomotion up the incline. The observations are made for slope angles of -4, -2, 0, 2 and 4 degrees.

B. Experimental Results

The experiment is motivated by the philosophy of morphological computation i.e. an attempt to design a robot that has complex system dynamics and is capable of producing desirable complex outputs when given simple actuation. From the experiments, we obtained the following two results.

1) Inching and Crawling Locomotions: Upon actuating the robot on flat experiment surface ($\theta = 0$), the robot displayed two distinct locomotion patterns that depended upon the phase gap ϕ. The first kind of locomotion involved propagation of a wave with the robot length as the wavelength as shown in Figure 8(a). Here, the red lines denoted the contact surface, and $T = 0.3$ s, $T = 0.5$ s figures indicate the wave where the two points of contact are the end of the robot. This locomotion pattern is referred to as inching. The other locomotion pattern, referred to as crawling, involves propagation of energy wave with wavelength that is approximately half of the robot length. Figure 8(b) shows the robot where the length of robot off the ground is approximately half of the robot length.

Figure 9 shows the distance traveled for difference phase gap ϕ. The error bars indicate standard deviation for last

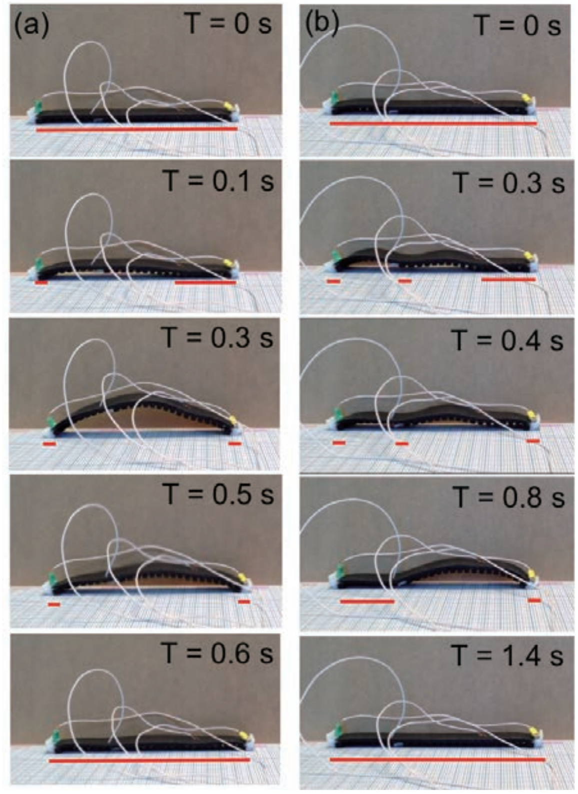

Fig. 8. Locomotion behaviors of (a) *Inching* and (b) *Crawling*. Inching gait can be observed when phase gap ϕ is 0.1 s and crawling gait can be observed when phase gap ϕ is 0.3 s. The red bars indicates the contact faces between TangoBlackPlus and the ground.

4 trials.[5] As evident from Figures 8 and 9, the transition from inching motion to crawling motion is observed after the phase gap of $\phi = 0.2$ s. The inching locomotion speed is observed to be greater than crawling locomotion speed. This results indicate that variation of friction with change in body shape, propagation of energy wave along the soft material of the body, and energy wave actuation regions (overlapped design of SMAs) perfom some of the prominent computations that have been embedded into the morphology of the robot.

2) Robust locomotion on variable friction conditions: Next, the effective friction of contact surface was varied by changing the inclination angle θ of the locomotion surface. The plot of the variation between -4 to 4 degrees is shown in Figures 10 and 11. Interestingly, inching locomotion gait was observed for phase gap less than $\phi = 0.2$ s for all the locomotion surfaces with observable change in locomotion speed. On an average, the inching motion displayed greater speed than crawling motion. For the tilt angle of $\theta = -4^o$ crawling speed was, expectedly, greater than inching speed. However, for the tilt angle of $\theta = 2^o$, the maximum crawling speed was greater than maximum inching speed. The robustness of the inching and crawling motions are observable as

[5]Data of each initial trial is eliminated, since the initial motion defers from movement of the last four trials. This can be thought that the robot need some warm-up time to heat SMAs to generate stable motion.

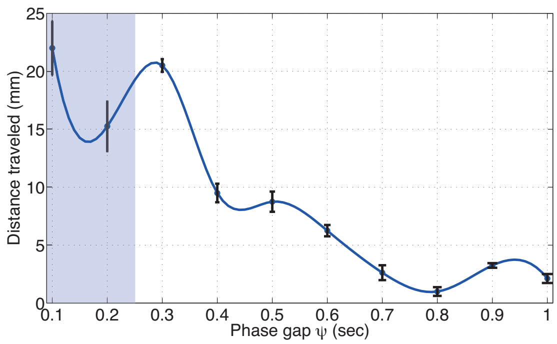

Fig. 9. Distance traveled by the robot in 10 s when the experiment surface is at zero inclination ($\theta = 0$). The robot displays change in locomotion behavior from inching (light blue area) to crawling as the phase gape ψ is increased beyond 0.2 sec. The error bars indicate standard deviation for last 4 trials.

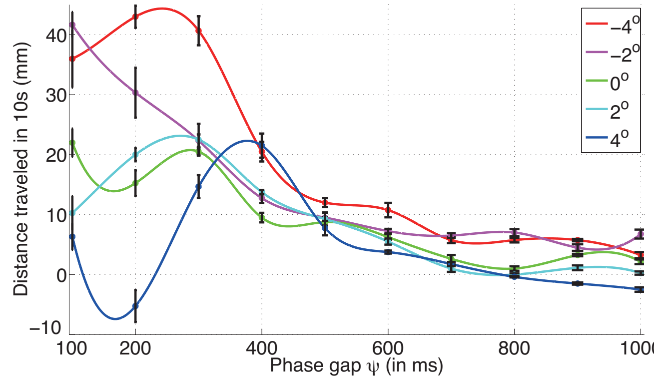

Fig. 11. Plot of robot speed vs phase gap for different inclinations of experimental surface. The error bars indicate standard deviation for last 4 trials.

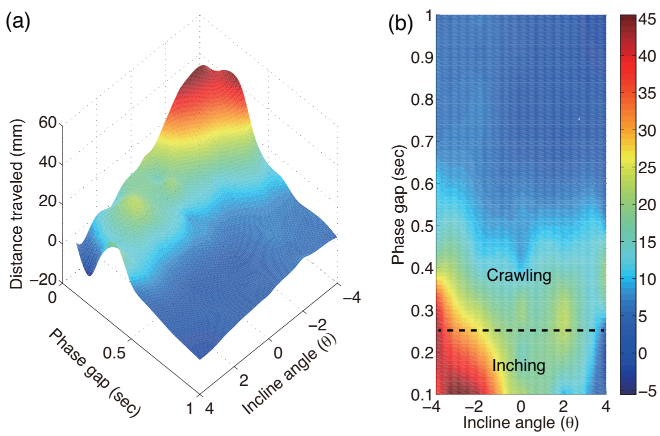

Fig. 10. (a) The performance of the robot as the inclination of the experiment surface is varied. (b) In the plot of change of phase gap vs change in effective friction (incline angle), the transition of locomotion pattern is indicated. It can be observed that for $\theta = 2^o$, maximum crawling speed is greater than maximum inching speed. The crawling speed for phase gap $\phi = 0.4$ sec remains almost same for change in effective friction of surface of contact. This displays the robustness of the crawling locomotion gait.

the effective friction of the surface is varied.

IV. Conclusion

The highly deformable 3-D printed soft robot (PS robot), discussed in the paper, was a successful attempt to embed complex computations into the robot morphology and obtain a complex physical and functional system (plant). This complex plant, given simple actuation, produced complex and robust gaits including inching and crawling. The soft body of the robot allowed waves of deformation to propagate during each cycle of actuation. To address the challenge of controlling friction, despite the light body weight of the robot, a novel variable friction contact point was designed. This mechanical design allowed the robot to switch its friction with the ground on the leg as the robot part deformed. Because these changes can be made at different times in different locations on soft robots, it is possible to generate directional movement. This general concept can be more fully exploited in future designs to allow the robot to adapt to different substrates and to move in different orientations. The fabrication of the robot was easy, quick, and economically cheap, thus, allowing fabrication in large numbers with ease.

V. Future Work

The successful display of morphological computation in soft robots opens gates for greater research in design of soft robots that are capable of locomotion which includes steering. The optimal design of the legs for locomotion needs to be explored. The use of tethers/strings (winded/un-winded by motors) instead of SMAs can be an alternative mechanical design especially for bigger soft robots. The waves of deformation were damped by the resilience of soft material used for the chassis. It is assumed that changing the material properties (e.g., extensibility, elastic modulus, and viscoelasticity) will have a major effect on the propagation of these deformations. The resulting interference is expected to result in richer locomotion behaviors due to the non-linearities of phase gap and amplitude. It is also desired to explore how sensors can be embedded into the robot so as to maintain the soft, complex nature of the robot.

The modeling of such robots as deformable and continuum robots and other tools needs are to be explored. Such modeling will is for estimation of model parameters using various machine learning technique. This will be beneficial to obtain richer information about the robot in real time, in complex environments and building simulation platforms for better robot design. This will also allow for closed loop control of the robot, easier maneuvering of obstacles, and so on. Finally, the variation of design parameters (e.g., placement of SMA coils, actuation voltage, etc.) also needs to be explored.

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