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Conceptualization and Fabrication of a Bioinspired Mobile Robot Actuated by Shape Memory Alloy Springs

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CONCEPTUALIZATION AND FABRICATION OF A BIOINSPIRED MOBILE ROBOT ACTUATED BY SHAPE MEMORY ALLOY SPRINGS

by

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ABSTRACT

This work is an experimental study and fabrication of design concepts to validate the feasibility of smart materials and their applications in bio-inspired robotics. Shape-Memory Alloy (SMA) springs are selected as the smart material actuators of interest to achieve locomotion in the proposed mobile robot. Based on a previous design of the robot, this work focuses on both implementing a new locomotion concept and reducing size and weight of the previous design, both using SMA based actuators. Objectives are met in consideration of the conceptual mechanics of circular robot locomotion.

The first prototype is a variation of the original design. It consists of a soft, rubber outer shell with three intrinsically attached diametric SMA springs that deform the outer shell during contraction and relaxation. The springs were provided with electrical current in patterns to produce deformation needed to generate momentum and allow the robot to tumble and roll. This design was further improved to provide more stability while rolling.

The second design concept is a modification of our previous design leading to reduction in size and weight while maintaining essentially the same mechanism of locomotion. In this case, the SMA springs were externally configured between the end of equi-spaced spokes and the circular core. Upon actuation, the spokes function as diametrically translating legs to generate locomotion. These design concepts are fabricated and experimented on, to determine their feasibility, i.e. whether rolling/tumbling motion is achieved. The scope of the project was limited to demonstration of basic locomotion, which was successful. Future work on this project will

address the design of automatic control to generate motion using closed-loop sensor-based actuation.

I would like to dedicate this work to my family, advisors, and friends who never stopped believing in my potential and provided me with endless encouragement and support.

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INTRODUCTION

Biology-inspired robotics is an area of research that has propagated due to these biomimetic systems offering a vast range of new characteristics such as increased degrees of freedom, high energy density, smaller footprint, and component simplicity. Consequently, investigators test and improve upon these attributes to enhance fields such as medicine, space exploration, and surveillance. The medical application in particular is the target for a mobile, undulating microrobot in hopes that it would benefit medical imaging or drug transport and delivery systems. This thesis is an experimental work that expands on work previously produced inspired by Spherobot [1, 2]. Although derivative of the prototype developed by E. Steffan and T. Das, the work described herein both challenges the approach and suggests an alternative to the design concept for a circular robot. The purpose of both design ideas for a bio-inspired robot is to use smart material technology that will make a miniaturized robot more feasible.

Theoretically, by applying smart materials to the design, the robot can maintain simplicity found in nature to generate motion in a rolling fashion while still utilizing diametrically-placed spokes as proposed in early research conducted by T. Das. In this thesis, the author describes the motivation and objective behind this work, explains the locomotion mechanism proposed, and discusses two approaches in which locomotion can be achieved using soft actuators and materials. To test these approaches, the author fabricated the two conceptual designs discussed, then compared the experimental outcomes of both designs followed by a description of future work required for development on the micro scale.

Motivation

The work described is motivated by the study by E. Steffan. The study explored the locomotion of circular robots as inspired by neutrophils [2]. Neutrophils are found in the highest quantities and mobilize by slowly rolling on the surface of blood vessel walls. The rolling mechanism is initiated by the formation and breaking of chemical bonds between adhesive ligands on the cell surface and receptors on vessel walls [3]. Studies on the dynamics of neutrophil rolling model the molecular bonds as compliant springs and the environmental forces applied to the cell, namely hydrodynamic forces and torques, as the means of forward motion [3, 4]. Figure 1 shows a ligand-covered neutrophil cell subjected to the molecular and environmental forces in the circulatory system.

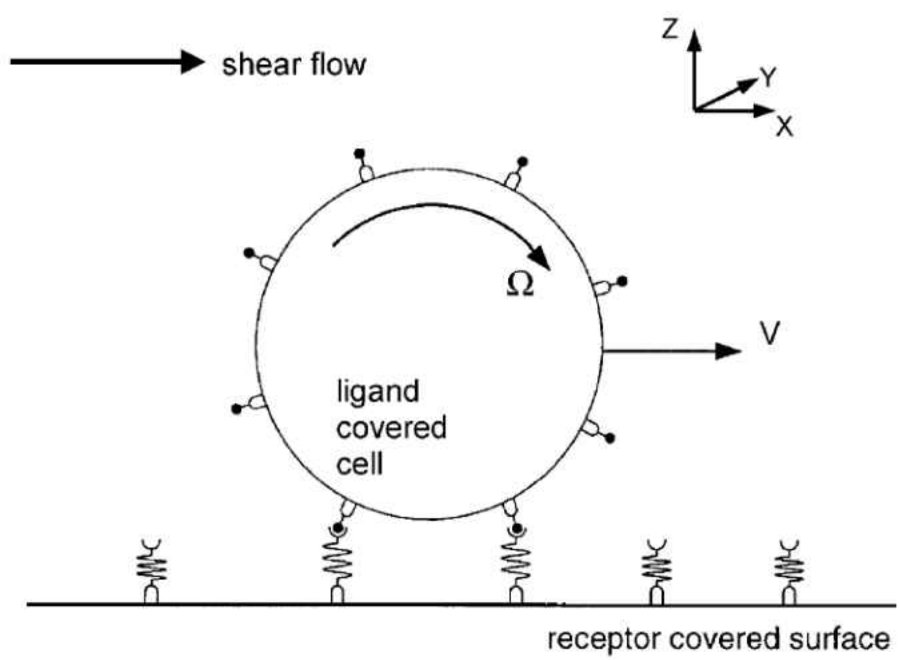


Figure 1 Neutrophil crawling along receptor covered surface subjected to shear flow in the blood vessels [4].

Since the long-term objective of this study is to develop a robot capable of interacting with a similar environment, the mechanism at which neutrophils roll along the surface of blood vessel walls motivated this thesis. Two design concepts are developed, fabricated, and tested in hopes of achieving miniaturization of the initial mobile circular robot worked on by E. Steffan and advised by T. Das at Rochester Institute of Technology. E. Steffan expressed that reducing the size of the prototype, as well, as simplifying the actuation mechanism would make the robot more feasible for application [2]. The following section provides a descriptive insight into this previous approach to a rolling, circular robot of which this thesis is a continuation of.

Previous Work

In "Locomotion of Circular Robots with Diametrically Translating Legs: Design, Analysis, and Fabrication", E. Steffan described the control of retractable spokes from a circular core and the mechanism at which the overall shape has the ability to morph. Based on the cellular locomotion achieved by neutrophils, a mechanism for a rolling robot was developed using geometry and the concept of imbalance caused by three articulating spokes through a circular core. The figure below describes the mechanism developed in the previous work.

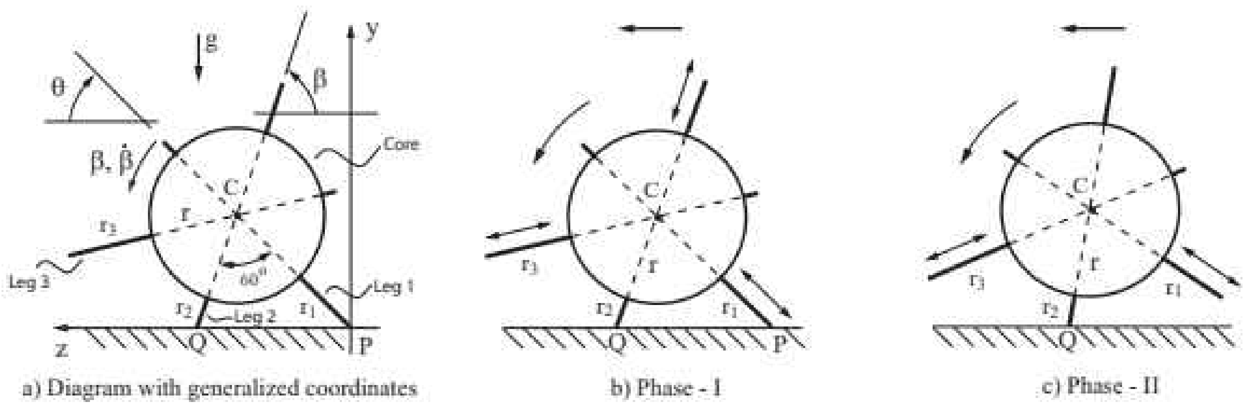


Figure 2 Rolling locomotion developed by E. Steffan at RIT [2].

Assuming that the overall surface area at the end of the spokes generated the deformable "shell", this study demonstrated how the change in surface shape caused an imbalance that allowed the robot to tumble. The concept of this type of undulating robot resembled that of amoeba, thereby inspiring its name: Locomotive Amoebic Device (LAD). The figure below shows how, as inspired by microorganisms and white blood cells, the robot achieved locomotion by deformation of an outer shell produced by intrinsic mechanisms.

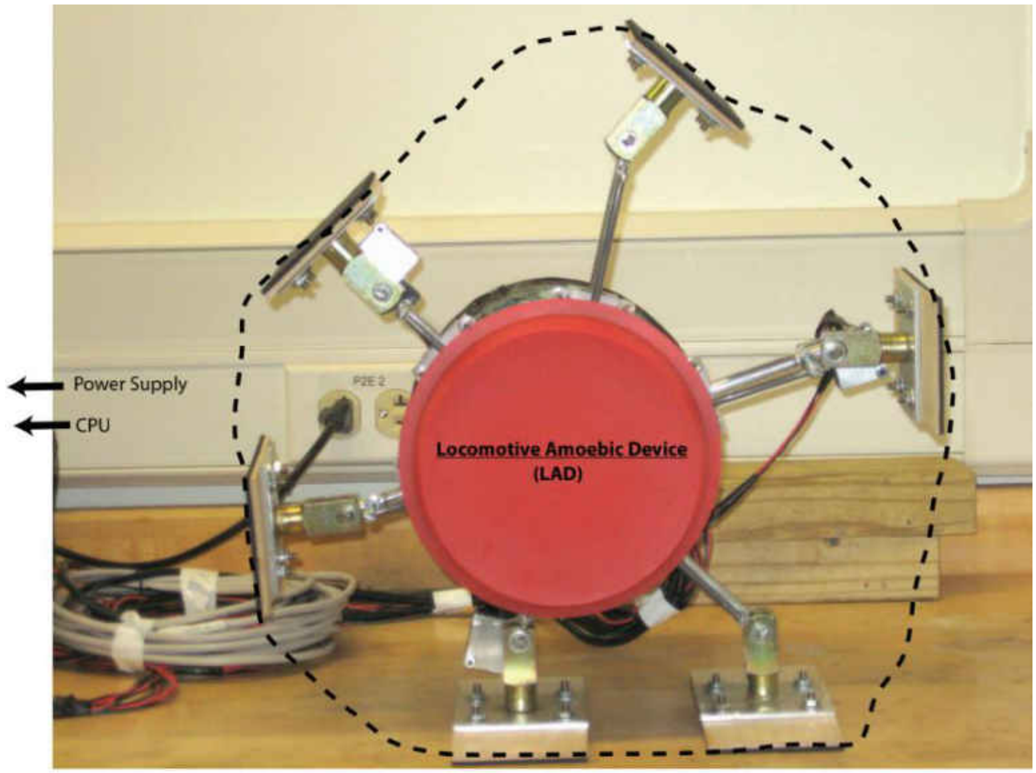


Figure 3 Previous robotic design as inspired by white blood cells. The deformation of the indicated "invisible" outer shell also mimics that of amoebic movement [2].

The author utilized three stepper motors along with a drive train to produce actuation of the diametric legs, potentiometer and encoder for feedback, and dSPACE to design a test bed to simulate experiments on controls and operation. Ultimately, the author in this study concluded that the prototype developed was capable of generating rolling locomotion, thereby giving some insight into a spherical version with N number of legs. The visualization of the spherical robot that incorporated E. Steffan's design is shown in Figure 3 below.

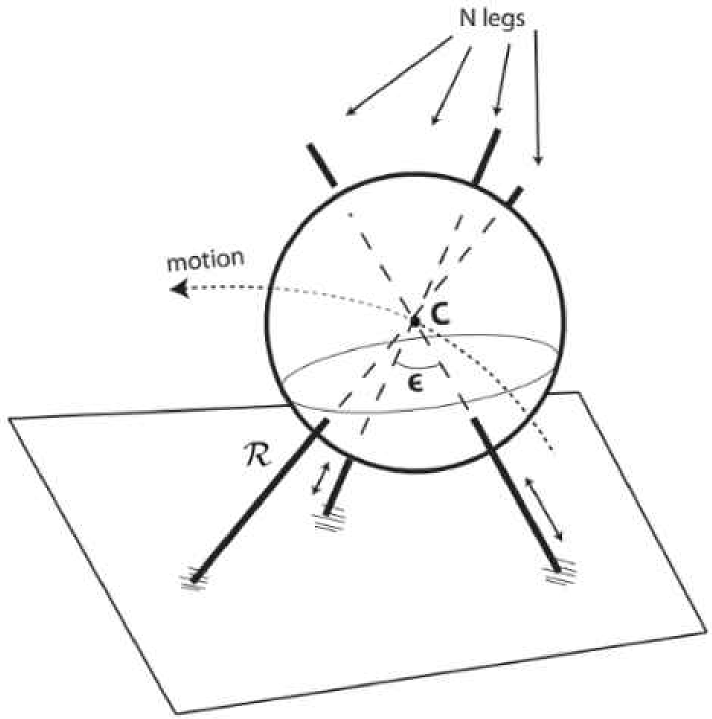


Figure 4 Visualized spherical robot design utilizes N retractable legs to produce undulating movement and promote rolling of the robot [2].

<u>Objectives</u>

The purpose of this thesis is to examine the approach taken by E. Steffan and rethink the technical approach used to create a bio-inspired circular robot. Through fabrication and experimentation, the author suggested two alternative methods of creating a circular robot that has improved characteristics. The author argued that these characteristics, a result of implementing soft robotic technology, would better support a spherical and miniaturized mobile robot for medical applications. The undulating LAD had an assumed "soft shell", however, the author challenged this concept by proposing that soft components that are physically incorporated into the design would easier meet the purpose of a circular robot inspired by nature.

Soft robots are a growing interest among investigators for medical applications, some of which include smart materials or actuators to create soft-bodied robots that do not rely on sophisticated control systems to respond and adapt to uncontrolled environments [5]. Smart materials present several advantages that would further improve the LAD design, some of which include energy efficiency, small footprint, and low weight. The objective of this work is to successfully fabricate and test a circular robot using smart materials that can generate deformation to complete several turns or tumbles in one direction, while simplifying the system such that miniaturization becomes an attainable feat. Before approaching this objective, a better understanding of how smart materials can be applied to small and lightweight robots inspired by nature was gained by reviewing similar explorations in literature. The following section describes the bioinspired soft robotic movement and reviews similar exploits in the fabrication of soft robotic systems.

An Overview of Soft Robotics

Traditional robots typically consist of high-weight, energy expensive, and rigid components that present several drawbacks in applications outside of manufacturing. To introduce creative solutions that require delicate interaction, dexterous handling, or difficult navigation through unpredictable environments, engineers have reflected on nature for inspiration. Most notably, soft-bodied organisms are deformable, conform to surfaces, can distribute stresses over larger areas, minimize the effect of impact forces, and adapt to unexpected interactions in surrounding environments or mediums. The use of soft materials presents the opportunity to simplify control systems and instead rely on the mechanical properties of soft materials to provide adaptability in locomotive robotic systems. Despite the obvious advantages of soft robots, these systems are also limited in their ability to support their own weight, exert large forces to generate motion, and the lack of standard control theory. As a result, these systems are only functional if they are built in smaller sizes or consist of solid frameworks or rigid intrinsic components [5].

Soft robots overcome these limitations by using soft materials with low modulus that articulate entirely as a continuum, reducing the force required to initiate deformation. Common elastomers such as silicone rubber are most commonly used by engineers to develop these soft, deformable systems. Furthermore, this avenue of robotics relies on alternative actuation methods not traditionally found in robotic systems that are also feasible for miniaturization by maintaining a small footprint. The three most common actuators in use are pneumatic actuators operated by compressed air or pressurized fluids to generate motion, dielectric elastomer actuators (DEA), and shape memory alloys (SMA) [5].

Implementation of pneumatic actuators has been a method of generating movement in robotic manipulators and grippers for several applications, including surgical intervention, since the 1950's [5]. High force and displacement are generated in these systems by using compressed air or pressurized fluid encased in elastomeric materials. The mechanism involves the sequential inflation of internal chambers inside of an elastomeric part in which force is generated by contact of one chamber to the next. Because this approach simply involves fluid and soft materials, several investigators have prototyped assistive devices, grippers, and manipulators that are safe to directly interact with humans. Figure 4 shows a rehabilitative glove design to use this technology to assist with hand opening and closing.

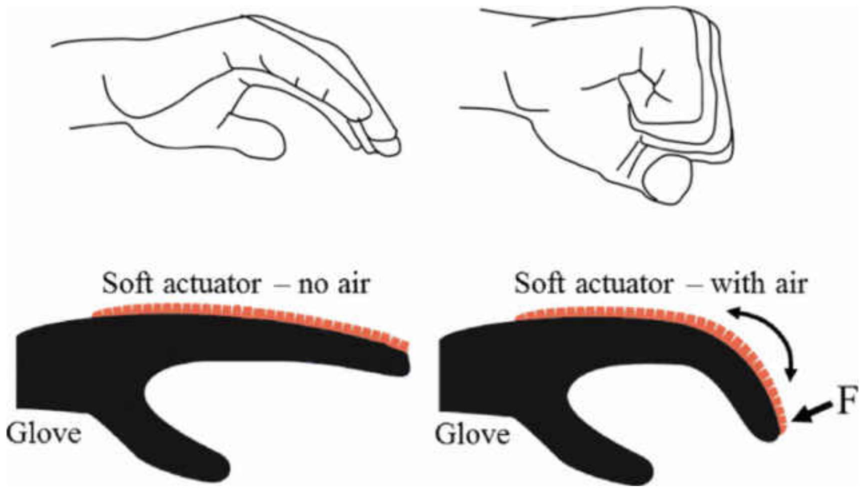


Figure 5 Rehabilitative glove design using pneumatic actuators to achieving gripping. As air is released into the chambers of the rubber actuators, they inflate and translate producing an overall force at the tip of the finger that assists in motion [6].

Despite the powerful actuation generated, pneumatics requires complex compressed air/fluid supply systems, high power, and seamless methodology to fabricate the custom elastomer polymer materials used.

DEA's, a class of smart materials, are elastomeric polymers that are actuated by generating an electrostatic interaction between two compliant electrodes with opposing charges. The actuation occurs due to the deformation of the polymer film placed between the electrodes [7]. Figure 5 shows how the voltage difference simultaneously compresses the volume of the film while stretching the area.

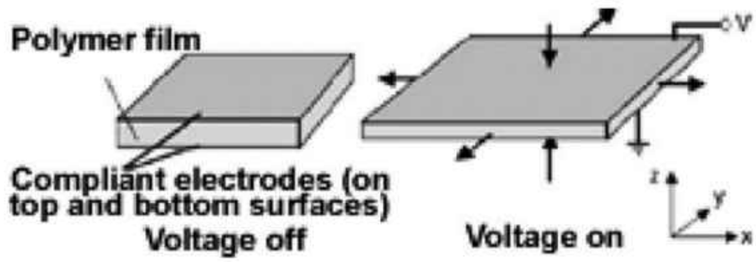


Figure 6 Compression of polymer film due to voltage difference between compliant electrodes on top and bottom surfaces of the DEA material [7].

Although these actuators present high deformation strain values, they are also limited in that a high electric field is required for operation. This alone would not make it a viable option, especially in the biomedical field, as it is unsafe to implement soft robots with high operating voltage. Furthermore, fabrication and customization of these materials is a costly and complicated process.

SMA's are another classification of smart materials that are often selected as actuators due to their high mass-specific force output. Due to their small footprint, engineers have been able to significantly minimize the size of their robotic systems and create actuation devices for locomotion, human assistance, laparoscopic manipulators, and automotive subsystems. As small-scale actuators, SMA's are able to generate large displacements and mass-specific forces, and even have large energy densities showing their promise as flexible actuation components in soft robots [5].

Examples of Bioinspired Robots Actuated by SMA's

Several examples of bio-inspired robots are present in literature and have been proven useful for applications that require execution of a delicate task, or careful movement and interaction with other objects, humans, or the environment. The devices reviewed in this section are SMA actuated, small-scale devices that provided insight for the work described in later sections.

In "A shape memory alloy based tendon-driven actuation system for biomimetic artificial fingers," Gilardi et al. developed an actuation system for hand prosthetic applications that mimicked the nature of muscle and tendon-driven movement in fingers. The proposed design consisted of an agonist-antagonist pair of tendon cables and one-way SMA wires that emulated the physiological behavior of the human finger [8, 9]. The figure below shows the artificial finger that is tendon-driven by remotely attached SMA actuators tested on a breadboard.

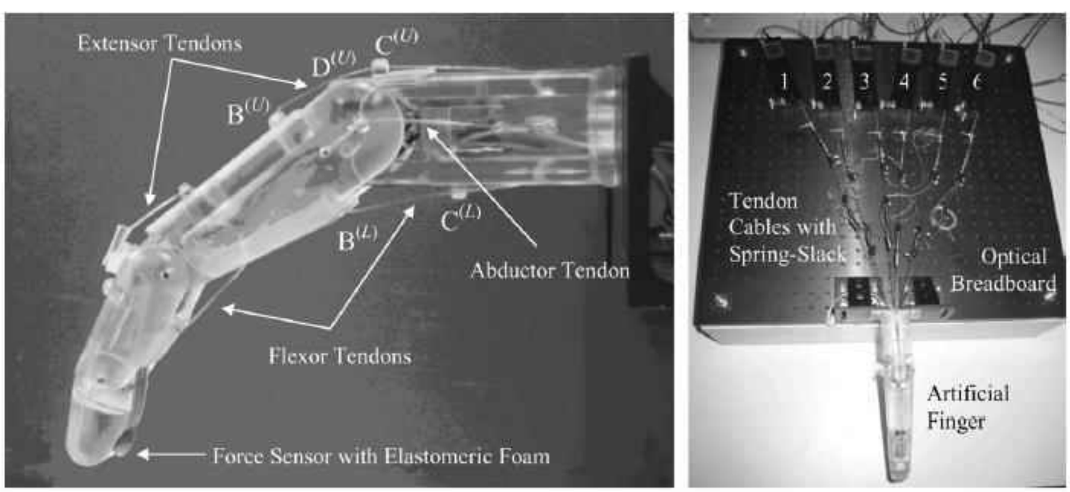


Figure 7 Tendon-driven actuator finger on breadboard test bed. The tendon cables are shown with SMA spring slack so that when contraction occurred, the springs tightened and pulled on the tendon cables initiating movement [9].

Authors in this study were not only able to produce a test bed for the artificial finger but were able to extensively study the heating and cooling behavior of SMA actuators. In doing so, a PID control scheme was developed using pulse-width modulation (PWM) in which voltage is switched between a low and high value, tuning the duty cycle during a fixed period of time [9]. Considering that there is a lack of general theory for SMA control, the methodology developed in this study provided an approach when implementing these smart materials in a deformable robot.

Aside from medical applications, investigators have also developed several nature-inspired robots to better understand the mechanics exhibited by certain species, further laying a groundwork for developing better control systems for soft robotic systems. For example, the micro trolley prototyped by Yao, et al. is inspired by insect motion most observed by inch worms or caterpillars. The authors of this study used an SMA spring actuator to generate locomotion [10].

The SMA actuator consisted of one SMA spring, a non-SMA spring acting as a bias to the SMA spring, and guide pillars. The SMA spring contracted upon heating thereby shrinking the length of the trolley. When heat is removed, the SMA spring relaxed in length and the bias spring stretched the length of the trolley, generating a forward motion [10]. This simple system successfully demonstrated how looking at nature may lead to the design of smaller-scale and efficient robots with several applications.

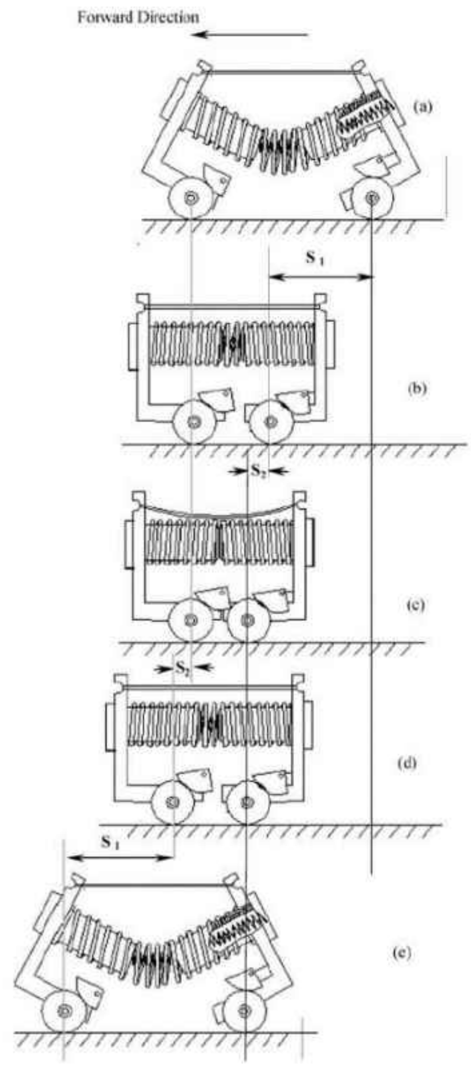


Figure 8 Locomotion mechanism for SMA actuated micro-trolley [10].

Figure 7 shows the mechanism in which the micro trolley generated forward motion. This study showed the importance of incorporating a bias force like a regular spring to hasten the cooling process of an SMA coil and generate motion.

Investigators have not only mimicked the motile characteristics of caterpillars by using SMA coils for their ability to perform as tensile actuators, but the application of soft materials have even more so recreated motion found in nature. Lin et al. successful created a soft-bodied robot that is actuated by SMA coils, however, it used the mechanical properties of the soft material to compensate for sensory feedback. This soft material is used to create the body of the robot by creating molds for silicone rubber parts. The material was cast such that features such as ventral legs, a head, and tail were included to aid in flexion, grip, and balance. Two axial tunnels were cast to house SMA coils along the ventral side as well. Once current was supplied to the SMA actuators, the body of the robot was able to morph in response to the coils contracting thus giving the robot the ability to ball up and roll [11]. The figure below details the design concept of the GoQBot that mimicked the crawling and ballistic rolling abilities of several caterpillar and larval species.

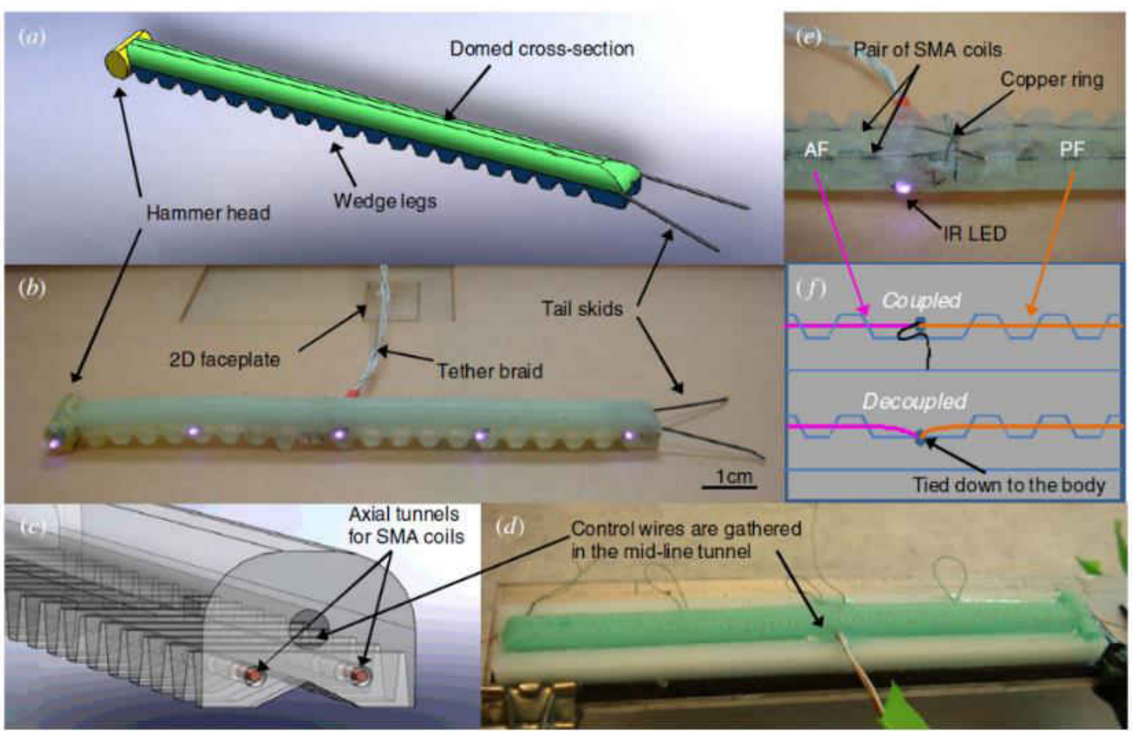


Figure 9 GoQBot design concept using integrated SMA coils [11].

In “Circular/Spherical Robots for Crawling and Jumping”, Sugiyama et al. explored the use of deformation in generating crawling and jumping motion in both circular and spherical robots. With the use of soft actuators like SMA coils, the authors of this study demonstrated how lightweight robots can overcome challenges such as recovery, adaptation to rough terrain, and unsafe interaction or impact with humans [12]. To accomplish this feat, Sugiyama et al. studied the mechanism behind the crawling by deformation principle. Starting with a stable geometry at rest, a body has zero gravitational potential energy and a perturbation causes a gradient in the gravitational potential energy. Self-deformation creates an unstable shape and changes this gradient thereby generating a rolling motion until the body is stable again. If this deformation is applied in patterns, an ongoing rolling or crawling motion may be achieved. Figure 9 shows how this principle is applied to soft, deformable bodies.

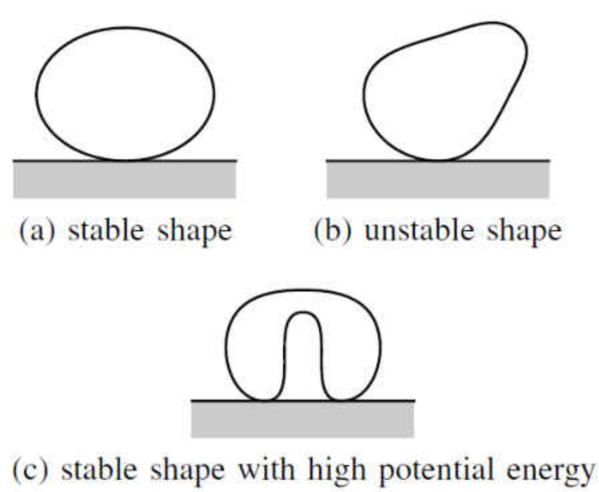


Figure 10 Deformation mechanism involving three different shape configurations [12].

Similarly, jumping is also accomplished by deformation, but the energy used to generate a jump is the storage and release of elastic potential energy [12]. Authors in this study prototyped two soft robots actuated by SMA springs using the energy concepts discussed. The figure below shows a simulation of the crawling circular robot actuated by eight intrinsically placed SMA springs that met at the center of the robot.

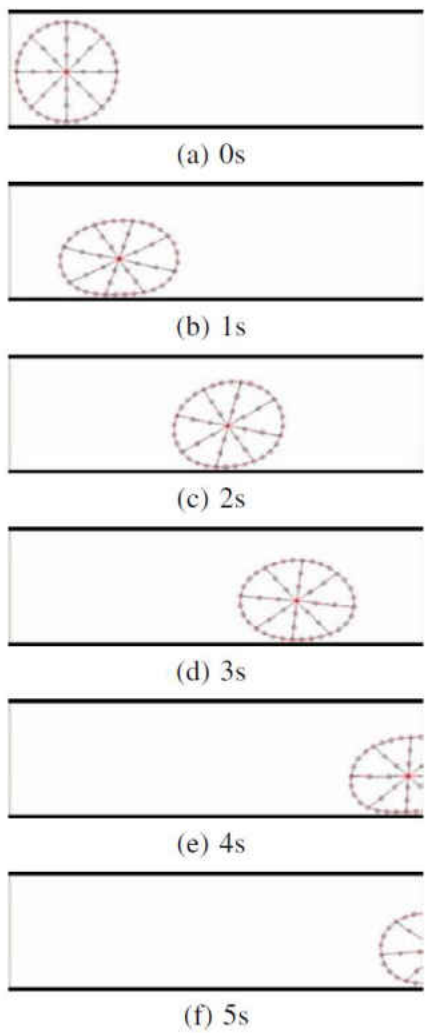


Figure 11 Simulation of crawling achieved by circular robot. Eight SMA springs met at the center of the robot and were activated in a pattern to achieve deformation and a forward rolling motion [12].

This study provided a basis for the deformation principle applied to the work described in later sections, and further shows how it is possible to implement both soft actuators and materials to overcome challenges met by rigid-bodied robotic systems.

THE MECHANICAL BEHAVIOR OF SMA'S

As described in the previous chapter, shape memory alloys are unique materials that display thermomechanical behaviors conducive to applications that require deformation. Some of these applications include civil engineering, medical devices, surgical robots, and locomotive robotic systems. As seen in literature, the typical SMA actuator as a subcomponent is either in the form of a wire, coil, or sheet. SMA's can either actuate on their own in low-force requirements, or work in a subsystem with other components that act as a bias to the SMA.

Before incorporating SMA springs into a design concept, the author studied the general mechanical behavior to better understand how these materials operate as actuators and what design considerations or constraints are presented as a result. Nickel titanium is the most common alloy used that displays the shape-memory effect. The shape-memory effect occurs in materials that can change phases due to applied heat allowing them to revert to their initial configuration. This temperature-dependent phase change occurs in the crystalline structure, typically a transformation that only occurs at one transition temperature or a range of temperatures. These phases in which these materials exist in are the austenite and martensitic phases. Exposure to temperatures below the transformation temperature transitions the material to the martensitic phase. When a mechanical load is applied during the martensitic phase, elastic properties are observed giving these materials the ability to stretch several lengths. When the material temperature is increased above the thermal threshold, the material reverts back to the austenite phase [13]. The figure below shows the relationship between temperature and the length of the material.

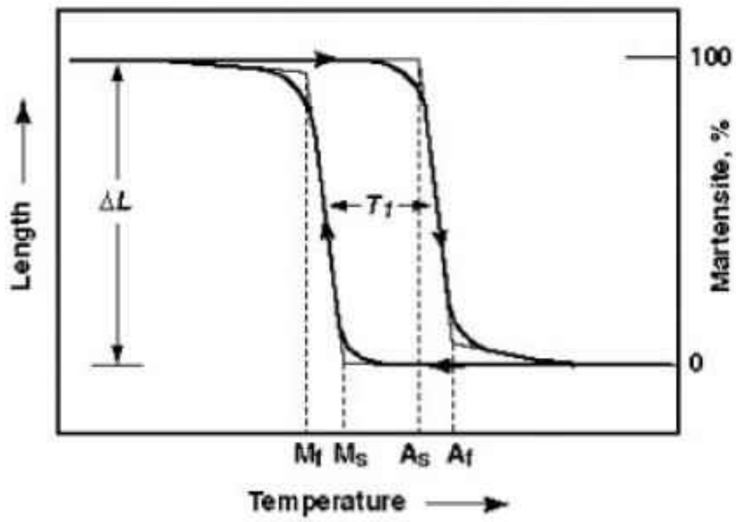


Figure 12 Temperature versus length of SMA material and the shift in phase as temperature increases [14].

For the purposes of this thesis, the author refered to several studies of the mechanical behavior of SMA coils. These studies detailed the transitional properties of SMA's and explained the stress-strain behavior of SMA coils using mechanical properties [13, 14]. Essentially, SMA actuators are best suited for low force and high displacement requirements due to their ability to relax at lengths more than twice their length. One thing to factor in is the cooling time required for SMA's. If fast responses are required in a design, the presence of a bias, heatsink, or some kind of cooling system for the wire or spring helps to reduce the cooling time. Without these measures, heat dissipates at room temperature and may not cool the SMA components with enough time for the intended operation. In addition, these materials exhibit nonlinear deformation and thermomechanical behavior. As a result, it should be noted that contraction time is directly related to the current supplied to these elements and the duration in which current is supplied to attain contraction. It is up to the user to develop control methodology to overcome these challenges. These methods are explained in the following chapter.

SMA ACTUATOR SELECTION

Several options for linear actuators were considered for the soft, circular robot developed in this work. Contenders included implementing hard components such as linear or micro servos that operated in a drive system to deform the soft material, as well as soft actuators discussed in literature regarding bioinspired soft robots. After careful consideration of soft actuation methods and methods most suited for soft robotic systems, SMA's were selected as the actuation of choice for the design concepts developed in the upcoming chapter. There were several reasons behind this decision: these materials are inexpensive, lightweight, conducive to miniaturization, and have a low energy requirement. Complex control systems are not required to operate SMA actuators, and they are available in the market as wires, springs, or sheets. These options allow for customization in size, shape, or configuration dependent on the design requirements of its intended system.

The objective of the work described in this thesis was to develop a circular robot that is soft, deformable, and capable of achieving a rolling motion. Much like the cytoskeleton of a white blood cell, internal spokes made of SMA wires or springs may function as the structural and intrinsic deformation mechanism of a rolling, circular robot. To determine the form of SMA required in this work, the author first experimented on a sample of SMA wire provided by Flexinol to test its ability to function as the actuator in this system. Flexinol, a subset of the DYNALLOY, Inc., is a brand that markets SMA wires for several small, DIY projects described in online forums. Recommendations on the selected technical specifications were made based on consultations with the manufacturer, DYNALLOY. The figure below shows the SMA wire sample provided by Flexinol.

Figure 13 SMA wire sample by Flexinol with specifications listed on the packaging [15].

Feasibility Test on SMA Wires

In the preliminary feasibility test, several considerations needed to be met to successfully experiment on an SMA wire. For the wire itself, a smaller wire diameter correlates to better cycle times due to the effect that heat dissipation has on contraction behavior and response. A possible countermeasure considered was pulsing current in short bursts to improve the wire's response to cooling. Regarding both mechanical and electrical attachments, crimping the ends of the wire is a common solution. The wire thickness changes through phase transition of the material, so solder and glue were not viable options for creating attachments. Other options included solderless terminals or machine screws and hex nuts. A bias force that is approximately 20% of the contraction force would provide the best cooling time at room temperature and would help the wire return to the lengthened state when cooled. This force could be provided by rubber bands, springs, gravity, another length of Flexinol wire, or hanging weights. In the actual prototype, an elastic shell would also could function as the bias force.

SMA wires and coils are available at two transformation temperatures: 70ºF and 90ºF. For the preliminary test on SMA wires, a length of the low temperature (LT) and high temperature (HT) wires were selected to undergo heating/cooling cycles with the goal of determining whether these wires would perform as actuators based on the following variables: displacement, contraction force, and heating/cooling times. The expectation was that both wires would heat upon supplying current and contract in length accordingly. Although the low temperature wire would require less heat thereby having a shorter cooling time compared to the high temperature wire, the pull force and deformation was not adequate for this thesis.

The 0.020 in diameter HT wire with a pull force of 570g, cooling deformation force of 228g, and required 660mA for 1 second contraction was thus selected to undergo these tests. The figure below shows the test bed for the SMA wires.

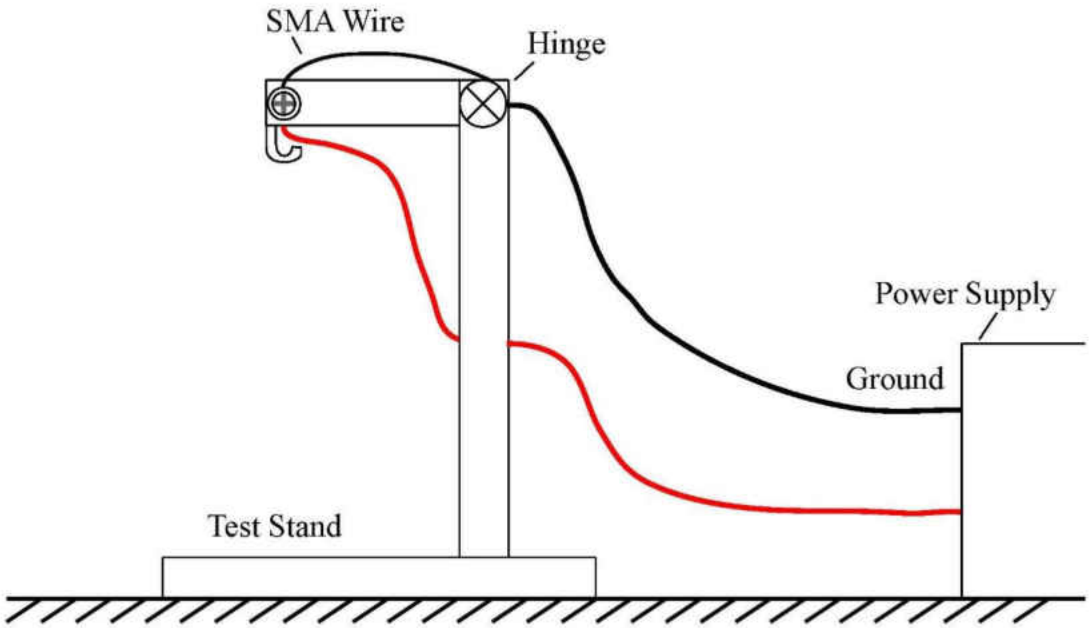


Figure 14 SMA wire test setup. The hanging masses were hung by the provided hook onto the test stand, then the supply voltage was switched on until wire length shortened and displacement of the hanging weight was observed.

The first trial with the HT wire pulled 17.1 g while heated by the power supply using 4.9 V and .66 A. The wire took 12.35 seconds to cool and stretch back to the relaxed length. The displacement of the hanging weight was approximately 1 cm. Subsequent trials showed cooling times of 9.53, 10.26, and 11.65 seconds with corresponding displacements of .5, .7, and .6 cm respectively. The outcome of this wire behavior experiment was that the SMA wire alone was not adequate to generate pull forces or displacements large enough to serve as primary actuators.

SMA Springs as Actuators

Since the SMA wires did not produce the deformation and pull force expected for main actuators in this work, the author referenced "Circular/Spherical Robots for Crawling and

Jumping" by Y. Sugiyama, et al. Investigators in this study were able to successfully utilize SMA springs as the main actuators to initiate the deformation and develop crawling circular and jumping spherical robots. In the circular prototype, eight SMA coils were radially configured inside of a soft, circular shell. Crawling behavior was achieved by implementing a contraction pattern that strategically activated a few springs per cycle. The coils used in this study, namely Biometal Helix, had the ability to generate 100 – 200% stroke of the length of the contracted BMX, had low current requirements, and generated 3 – 40 gf maximum force (depending on wire diameter) [12]. This study exemplified the benefits of using SMA coils to meet the objectives of this thesis, such as more displacement and pull force. As a result, the next phase of testing began on carefully selected SMA spring samples. The following section discusses the selection process of the spring's specifications.

<u>SMA Spring Technical Specifications and Selection</u>

Two sources of SMA springs were identified in the search for SMA springs. In "Circular/Spherical Robots for Crawling and Jumping", investigators utilized BioMetal Helix springs to prototype circular and spherical robots capable of rolling and jumping motions [12]. However, technical specifications and purchasing information were difficult to find on this product. After the author reviewed SMA spring products online, DYNALLOY, Inc. was selected to manufacture custom actuators due to the various design options available and easily accessed information on product services. To determine the optimal specifications of the springs for the robot, each wire diameter option had to be considered carefully. The figure from the DYNALLOY, Inc. website below outlines specification values for each spring wire diameter option offered.

Spring Wire Diameter in(mm), Outer Diameter in(mm)	SR Cold, SR Hot*	Displacement / Coil in(mm)*	Resistance on Straight Wire ohms/inch (ohms/meter)	Heating Pull Force** pounds (grams)	Cooling Deformation Force** pounds (grams)	Approximate*** Current for 2 Seconds Contraction (A)	Cooling Time 194°F, 90°C "HT" Wire**** (seconds)
0.020 (0.51), 0.136 (3.45)	6.5, 3.5	0.06 (1.5)	0.11 (4.33)	0.536 (243.3)	0.215 (97.32)	3.4	15.0
0.015 (0.381), 0.10 (2.54)	6.5, 3.5	0.04 (1.1)	0.21 (8.27)	0.307 (139.3)	0.122 (55.72)	1.9	9.0
0.008 (0.203), 0.054 (1.37)	6.5, 3.5	0.02 (0.6)	0.74 (29.13)	0.089 (39.3)	0.035 (15.94)	0.7	3.0

Figure 15 Expected specification values for three options of spring wire diameter as made available by DYNALLOY, Inc. [16].

Larger displacements ultimately would lead to more deformation, thus specifications of the spring with the largest wire diameter, 0.020 inches, were studied. The goal was to test an actuator that when configured into the prototype and operated would cause significant surface deformations. These surface deformations would change the gradient of gravitational potential energy and cause the body to tumble. A prototype with a soft, cylindrical shell about 4 – 6 inches inner diameter and diametrically configured SMA springs was conjectured to accomplish this rolling behavior via body deformation. Keeping this conceptual design in mind, calculations were done using the specifications provided by the DYNALLOY, Inc. website [16]. The solid length was found by multiplying the number of coils by the wire diameter. To get a desired diameter of approximately 4 inches, a spring with 0.020 inches wire diameter and 40 coils at a solid length of 0.8 inches can be stretched and configured in tension so that upon heating, contraction would cause the overall shape to deform. This was an approximate calculation, however, because the manufacturer disclosed that the springs may come with a few more or less coils. The image below shows an SMA spring less than 2 inches in length with requested 40 coils as delivered by DYNALLOY.

Figure 16 SMA spring as received from the manufacturer. This spring had not been tested on, thus is in its solid length pictured above.

Just prior to testing, one spring was used to determine the optimal voltage and current settings to heat the springs without causing burnout. 2V and 1A was the optimal setting on the power supply to prevent permanent damage to the SMA springs while stretching each end of the spring and contracting it fully for several trials. During these cycles, it was observed that after initial heating, the spring elongated drastically while cooling then was able to contract back to the initial length even after several cycles.

The specifications reported a heating pull force of 243.6 grams, thus to run preliminary feasibility tests on the springs, the author conducted simple trials with hanging masses. The diagram below depicts the test setup used to conduct this experiment.

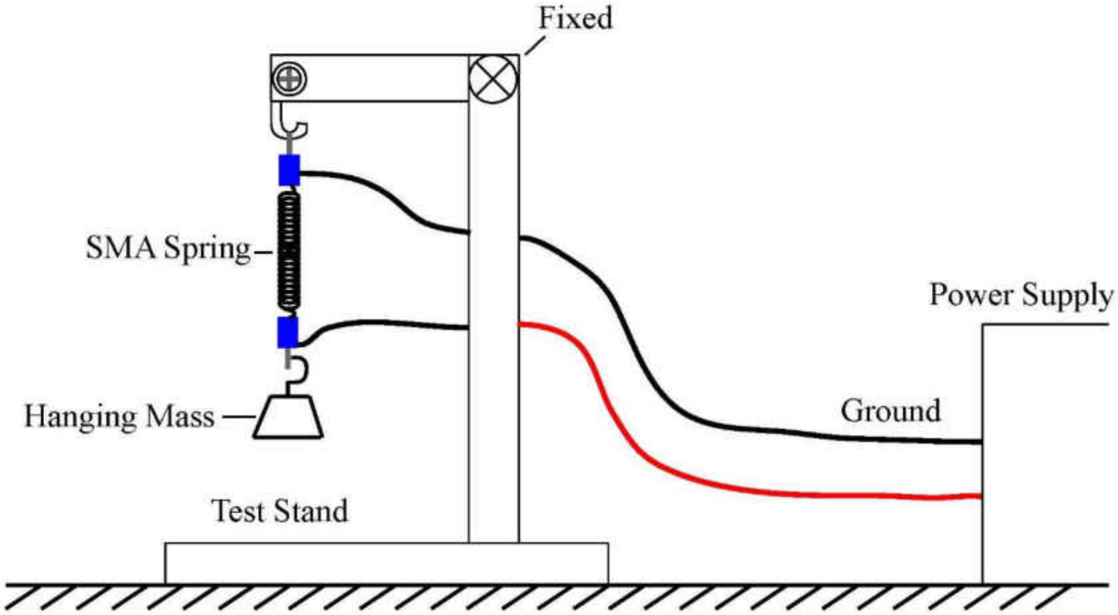


Figure 17 Setup used to conduct initial performance tests on selected SMA springs.

Results of the displacement test using 100 g, 150 g, and 200 g masses were recorded for five trials each and the figure below shows that the springs consistently displaced the same amount each cycle with very little error despite the mechanical loading applied. The displacement increased with applied load due to the fact that the springs stretch multiples their length prior to heating. Thus, more added weight meant a longer stretched length and a larger displacement upon heating. The heated length was consistent throughout all trials and added weights.

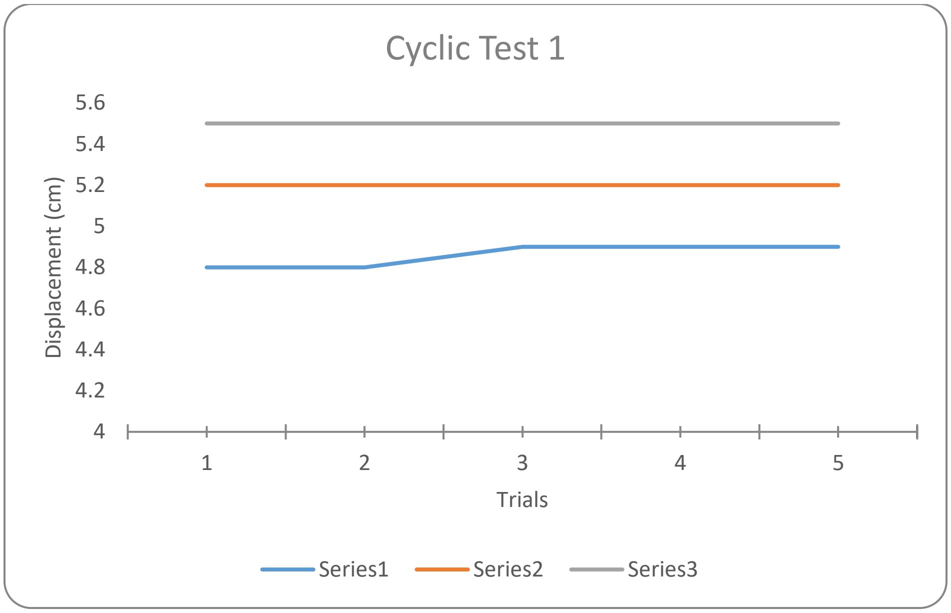


Figure 18 Results of cycling experiment using 100g, 150g, and 200g hanging masses in Series 1, 2, and 3 respectively.

To develop a control scheme for spring contraction, the contraction time, or the time it takes to fully contract, was measured to understand the contraction behavior and what kind of control scheme is necessary. Additionally, it gave the author insight on the correlation between activation time and the response generated by the springs. The results of the timing tests are shown in the figure below.

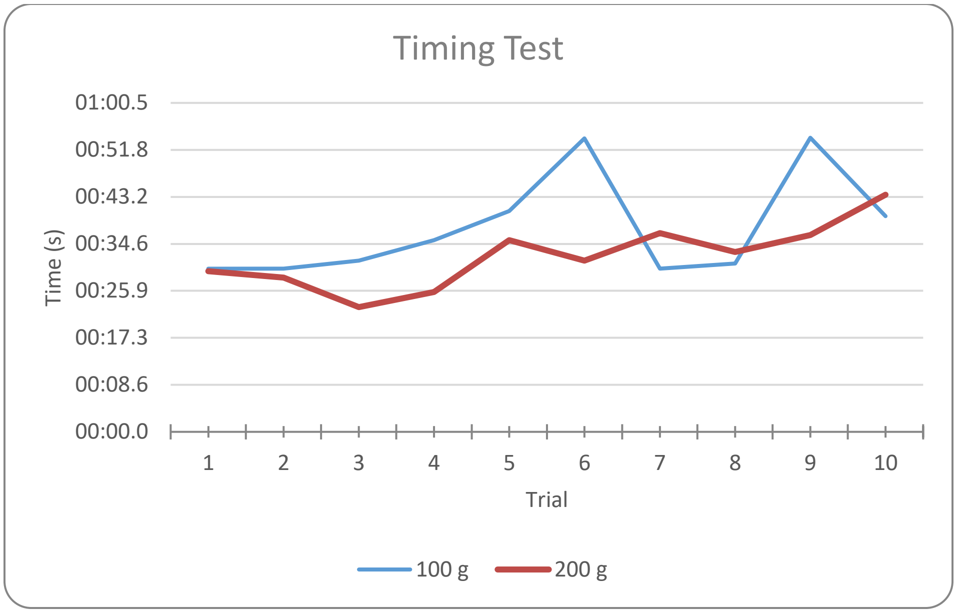


Figure 19 Results of contraction time experiment using 100g and 200g hanging masses.

As shown in the results, contraction length was consistent while contraction time varied a lot more; thus, waiting for the springs to displace completely to full contraction under mechanical loading might not be optimal to achieve faster response times to generate rolling. However, because a soft shell is easily deformable, shorter pulses of current to the springs would produce enough deformation despite the fact that the actuators would not contract fully. These studies concluded that SMA springs would be selected as the main actuator in the fabrication of a bioinspired, soft-shelled circular robot.

INTRINSIC ACTUATION METHOD (IAM)

Details of the Design Concept

For a first prototype, testing a cylindrical shape is ideal to evaluate the SMA spring effectiveness for the overall project goal. This cylindrical shell shall contain three SMA springs placed diametrically, equally spaced with respect to each other, and stretched from the solid length to the inner diameter, three inches.

It was hypothesized that if the springs were activated in the correct pattern, due to equal distribution, an internal mechanism of deformation would cause the robot to tumble and roll. A power supply was used to activate the springs and determine the activation pattern that would produce the tumbling motion. This initial testing also would show if the concept was feasible based on the performance of the springs and their ability to produce a rolling prototype. If the displacement of the springs was adequate enough to deform the body into an unstable shape causing it to tumble, continuous and patterned activation would in turn cause the model to roll forward.

The selected material for the shell was silicone rubber, a common rubber used in soft robotics applications. Much like the SMA actuators, silicone has the ability to stretch more than its actual shape and revert back [5]. In the market, there are several options for the type of rubber, however, for the purposes of prototyping and proof of concept, door stopper material was purchased to act as the soft shell. This silicone material was pliable enough to deform as needed, but rigid enough to maintain a circular, undeformed shape. Design drawings are found in the following section.

Drawings

Figure 18 shows the design concept of the intrinsic, diametric concept for a bioinspired, circular robot. The three springs were offset and denoted as the front, mid-section, and back springs or Spring 1 (S1), Spring 2 (S2), and Spring 3 (S3) respectively.

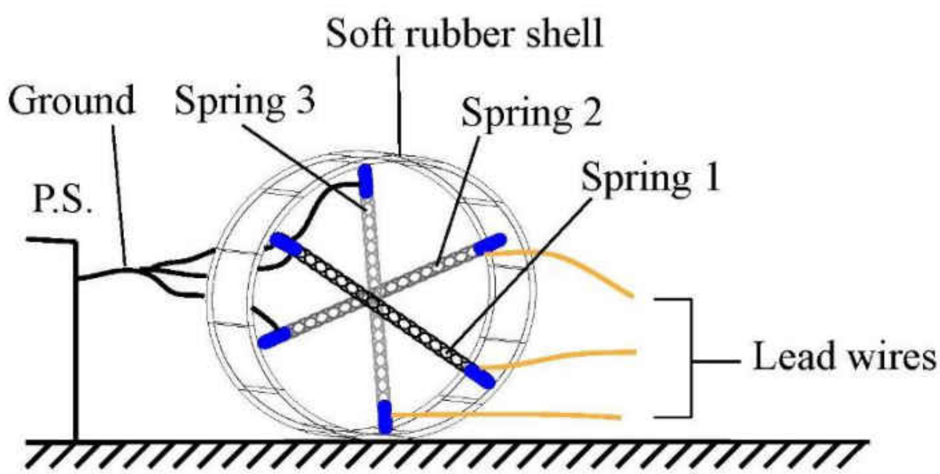


Figure 20 Pictured is the first prototype with a soft shell and three diametrically placed SMA springs.

The activation of S1 is the initial phase of the rolling mechanism which would transform the shape from a stable and at rest position into an unstable position. In this phase, the gravitational potential energy would increase, thereby causing the shape to roll forward and make another contact with the surface. The next phase would begin when heat is removed from S1. During this phase, the shape would need to be perturbed again, thus the next deformation would need to act as a bias to stretch the cooling S1 and increase the gravitational potential energy once again. S2 would be activated immediately after heat is removed from S1. Once S1 is cooled and completely stretched back to its initial configuration and S2 is contracted enough to initiate another tumble, the heat would be removed and applied to S3. One full cycle consists of a total of four phases as shown in the figure below.

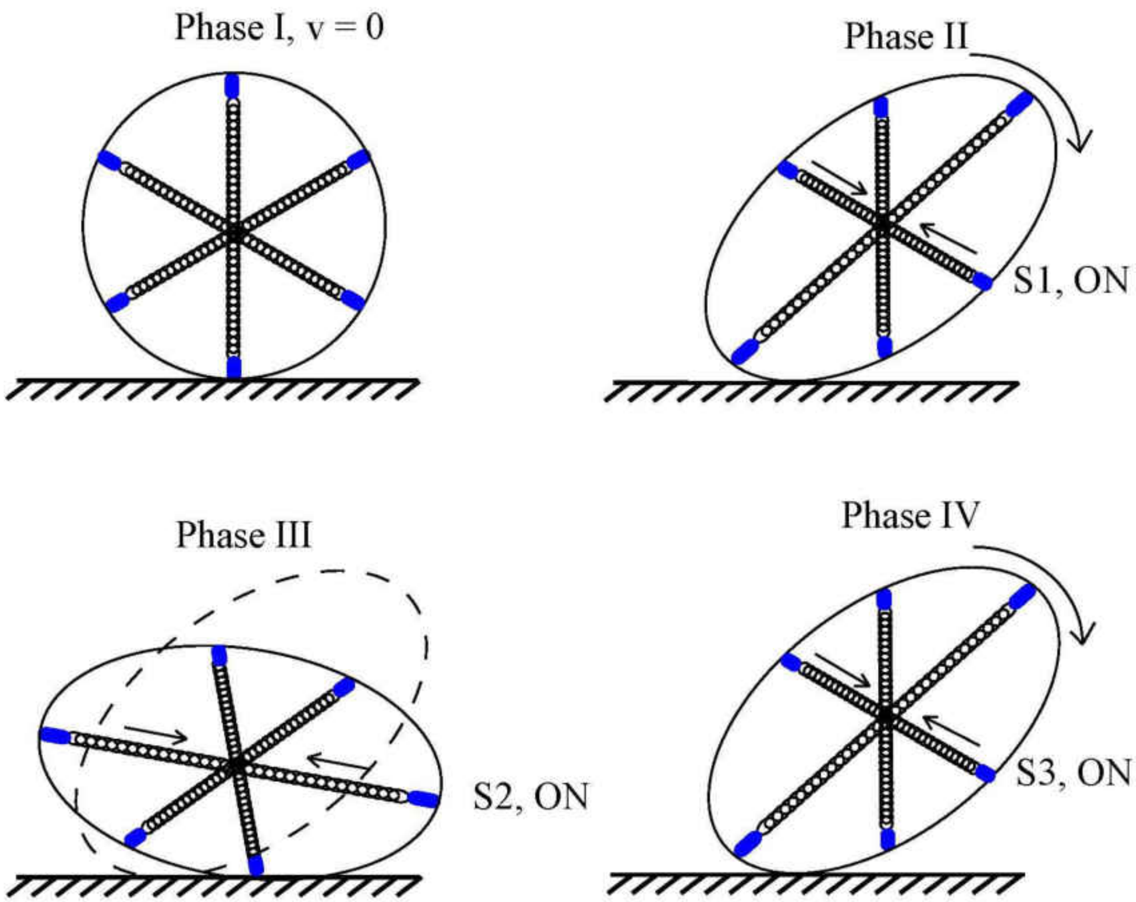


Figure 21 Hypothesized contraction pattern of the prototype. If this cycle is repeated, continuous rolling would be achieved.

Components and Materials

The materials used for the testing and prototyping process are outlined as shown in the table below.

Table 1 Table of Materials for Prototype

#	Item	Vendor	Quantity
1	Springs w/ 40 coils of 0.020" Flexinol Spring	Dynalloy	4
2	Ace Industrial Ring Terminal Vinyl 10 Red	Ace Hardware	2
3	Gorilla Super Glue	Home Depot	1
4	Weatherstrip	Home Depot	1
5	Omron General Purpose Relays SPST - NO Sealed	Mouser Electronics	1
6	Arduino Uno - R3	SparkFun	1
7	Hook-up Stranded Wire - Red (22 AWG)	SparkFun	1
8	IRWIN VISE-GRIP Multi-Tool Wire Stripper/Crimper/Cutter	Amazon	1
9	Springs w/ 40 coils of 0.020" Flexinol Spring	Dynalloy	3
10	Omron General Purpose Relays SPST - NO Sealed	Mouser Electronics	1
11	Springs w/ 40 coils of 0.020" Flexinol Spring	Dynalloy	6
12	Ring terminals, gorilla glue, insulation rubber strip, fasteners	Ace Hardware	1
13	SPST Relays	Mouser Electronics	6
14	Ring terminals	ACE Hardware	1
15	Fasteners, terminals	ACE Hardware	1
16	Fasteners, rubber strip	ACE Hardware	1
17	Fasteners	ACE Hardware	1
18	Springs w/ 40 coils of 0.020" Flexinol Spring	Dynalloy	1
19	Springs w/ 40 coils of 0.020" Flexinol Spring	Dynalloy	1

Prototyping

Prior to prototyping this design concept, the problem of SMA attachment to an insulated and elastic shell had to be approached. To accomplish this, the author used crimp attachments on each end of the SMA terminals to provide a means for adhering to other components in the prototype as well as to provide an interface between the actuators and other electrical components. A lead wire was also crimped onto each end of the SMA springs.

Next, the functionality of the rubber material purchased would be tested after the ring terminals were bent at a 90^o angle and gorilla glue was used to adhere the insulated portion of the terminals to the inside of the circular shell. If one layer of the shell material did not reliably deform without failing to roll the robot forward, another layer of rubber material was layered over the initial layer using gorilla glue.

After manually testing the shell thickness, the springs were secured to the shell using more reliable mechanical attachments from the ring terminals to the shell: hex nuts and screws. Figure displays how the SMA springs were mechanically attached to the shell and also shows the electrical attachments from the prototype to the power source. The hex nuts were configured onto the inner surface of the shell and heads of the screws were adjusted such that these fasteners were flush with the surface to prevent any hindrances during the rolling process. Manual experiments involving the activation pattern and establishing a repeatable, rolling motion were then performed to prove or disprove the hypothesis in support of this design concept.

Manual Testing

The manual testing process of this design concept was performed using a power supply set at 2V and 1A. One end of the spring was exposed to the ground and the other exposed to the positive and held until contraction occurred. After a series of contact tests with the power supply leads, a slow response time was observed, and the expected rolling motion was not accomplished.

The optimal settings for the power supply were tuned through trial and error and the author found that the setting of 3.7V and roughly 1.5A worked best. Higher voltage and current settings allowed for faster spring response and shorter cycling periods for the actuators. Figure 20 below shows the test bed for manual testing on the model with three intrinsic SMA springs.

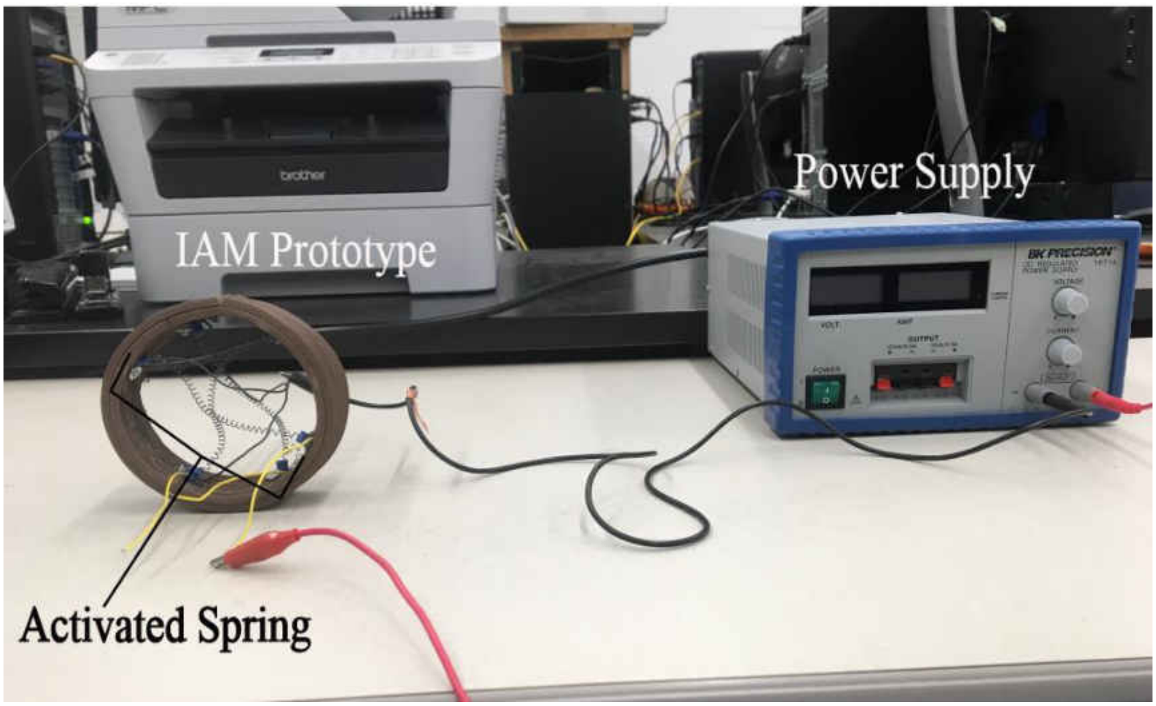


Figure 22 Manual test bed for prototype testing using a power supply.

With the robot at the resting state showed in Figure 20, the following activation pattern was used to produce rolling in one direction:

Table 2 Activation pattern during manual testing that initiated rolling.

SPRING	**1**	**2**	**3**
ACTIVATION	OFF	OFF	ON
	OFF	ON	OFF
	ON	OFF	OFF
	OFF	ON	OFF
	OFF	ON	

The resulting motion through manual testing is listed in Appendix B. These results showed that locomotion was possible, however, the activation pattern for deformation did not produce the expected movement as hypothesized during the conceptualization phase. Furthermore, once all three springs have been activated in turn and the pattern is repeated to observe a continued rolling motion, the shell did not recover due to warping on the sides as shown in Figure 23.

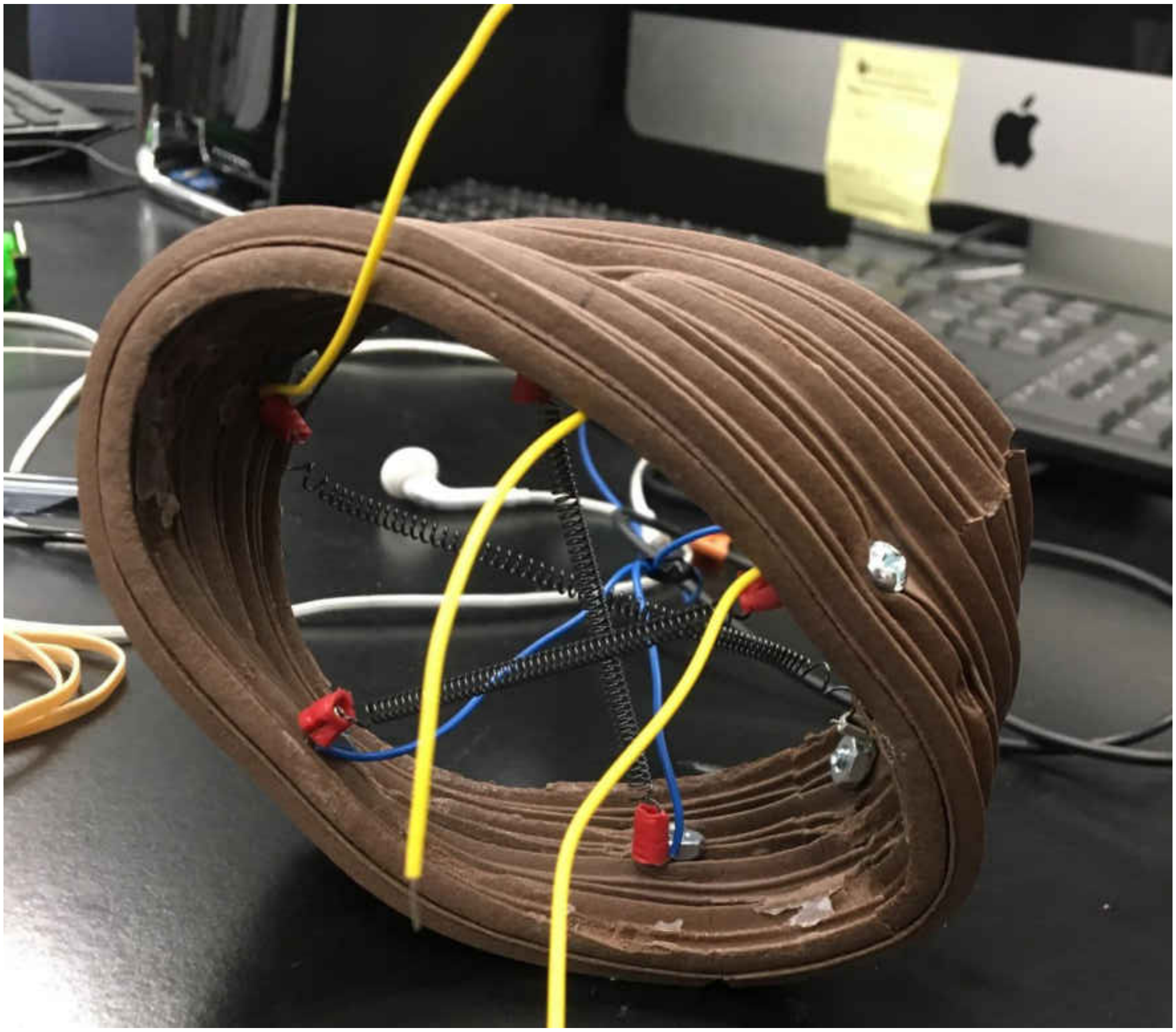


Figure 23 Warping on each end of the circular robot demonstrated after one cycle of rolling.

The pattern, once already begun, did not hold during continuous mechanistic activation, thus the results disproved the hypothesis. Further testing was anticipated using any the following considerations: the shell thickness was increased by one more layer of material to prevent warping and improve shell recovery; the width of the shell may be increased and more springs added that may be activated in parallel pairs to symmetrically deform the shell and stabilize the robot during rolling; a supplemental bias force such as a rubber band may be added if the shell improvements fail; or, if the issue is the manual testing process itself, a control circuit could be implemented to avoid error. It was decided upon to try two of these considerations and determine which one would meet the objective of the IAM design.

The following version of this design involved an increased shell width of 3.5 inches and six SMA springs. The concept of this design was to activate two springs in parallel to equally distribute the deformation of the shell and improve recovery after one full cycle. Figure 22 shows how the six SMA springs were configured using hex nuts and screws, offset with respect to the other.

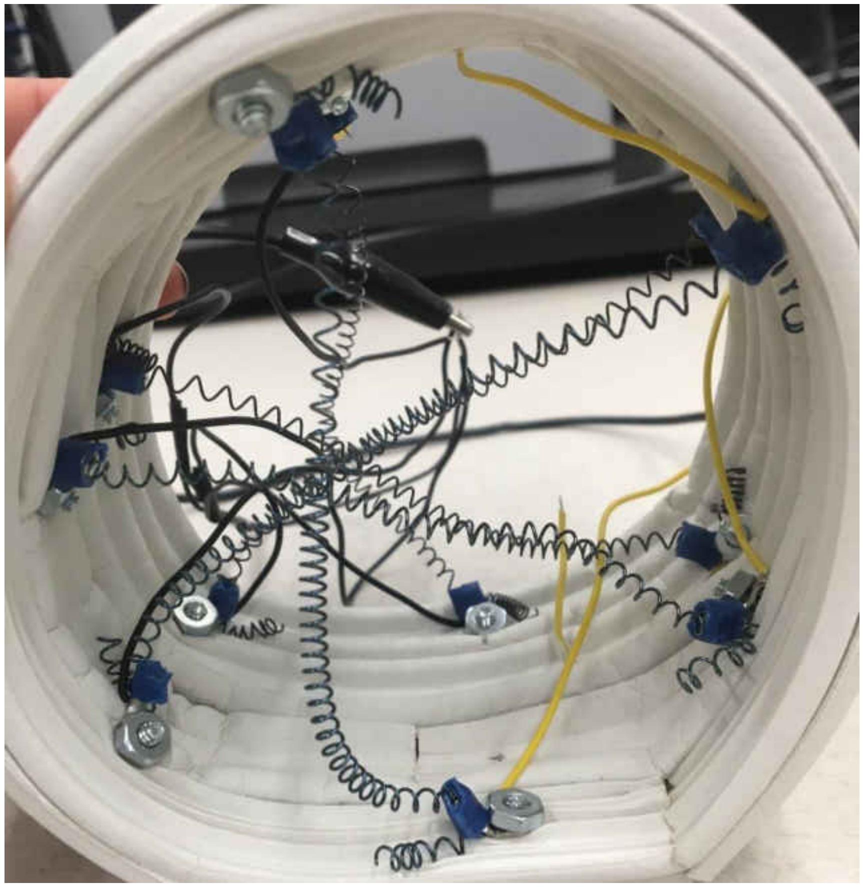


Figure 24 Version two of the first design concept with a wider shell and six SMA springs to generate deformation.

The springs, from front to back were named sequentially as springs 1 through 6 or S1 through S6. Thus, if parallel activation was the objective, then as S1 and S6 were first activated, heating S2 and S5 next would initiate the next phase in the rolling process. This would also hold for S3 and S4 for the next step in the activation pattern. This concept was tested manually and showed an improved shell recovery, as well as higher force outputs from the actuators. If automated, this process would occur in a smoother and more controlled manner. However, before developing a control system for six springs, a control standard had to be established for at least one or two springs as a starting point.

To establish smooth control and yield reliable experimental results, proper tests using a simple control circuit were performed on the first version of the prototype. Since the activation mechanism for the springs was as simple as switching current on and off from a source, relays were considered to switch the DC voltage from the power supply on and off based on a block diagram developed in SIMULINK. This would provide the opportunity to create timed pulses, adjust the frequency of the pulses, and then generate a generic C code that could be uploaded to a processor. The following section describes the control theory implemented and the simulation experiments conducted for use with the SMA actuators in this work.

Controls Theory and Implementation

As mentioned previously, timed pulses of current provided to the SMA springs are necessary to activate and deactivate the springs. In creating a circuit that would both provide current to and remove current from the actuators, the use of a switch or relay was considered. One SPST relay per SMA spring was first tested with one spring, then two SPST relays with two springs to develop a framework for a control system.

To remain within the scope of the thesis, experimentation on dSPACE using relays was performed and evaluated for the feasibility of the method developed in future work on an automatic and closed-loop system. To begin this process, a simple on/off experiment on one spring was performed using input from the user that underwent digital to analog conversion to either open or close the circuit. This input originated from timed pulses in a SIMULINK program using a pulse generator as the source block. For this first one relay/one spring test, an SPST relay by OMRON was purchased with 5V and 4 pins. The switching capability of the relay was 3A and 5A. After operating this first relay, a second relay was purchased and wired to another SMA spring so that the next phase of the control development could begin.

SIMULINK Model

An open loop program was generated in SIMULINK to test two springs and two relays. When the constant value was set to 1, dSPACE sent 10V through the DAC. Since the relays needed 5V to switch, a saturation block was placed between constant and DAC to saturate the values by half. Thus, if the constant was set to 1, the output would be half of 10V, the required switching voltage for the selected relay. Once this program was uploaded, the relay was able to successfully switch the circuit on and off as desired.

On sending voltage from dSPACE to more than one relay to control the spring activation, one relay would need to be open while the other remains closed, and they would need to alternate. To accomplish this, a method must be applied in the logic that would allow the signal sent to one relay to be high, at 5V, while the other is low, at ground. Thus, over some time interval, the two separate signals would be high while the other is low. Pulse width modulation, or PWM, was implemented to overcome this challenge. The interval at which the signal is high, or δ, was determined by thinking about the results of manual testing as a starting point. The delay, or ε, was implemented before and after a signal was high. Figure 23 shows an example of the PWM for a digital signal that would be sent from the user in dSPACE to the relay used for SMA testing.

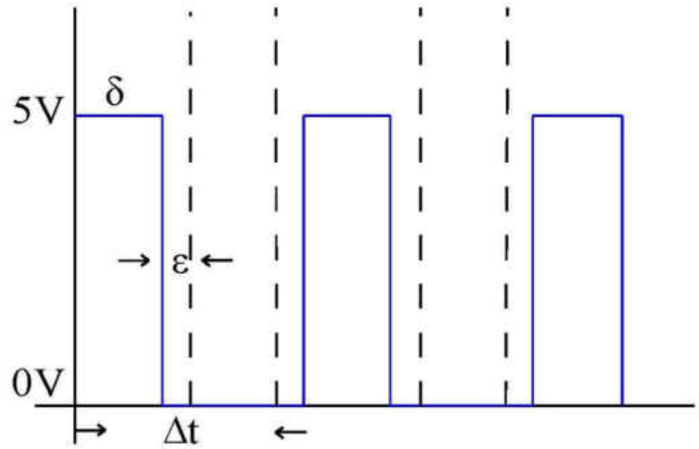


Figure 25 PWM for 5V relay over a period of time.

The period, or Δt, as shown in Figure 24 was the interval in which the signal goes from high to low and was calculated as shown by Equation 1. Once the period was found, Equation 2 was used to calculate the duty cycle, or the percentage of the period in which the signal is high.

$$\Delta t = 2\delta_1 + 2\varepsilon \qquad (1)$$

$$\frac{\delta_1}{2\delta_1 + 2\varepsilon} = \frac{1}{2 + (\frac{\varepsilon}{\delta_1})} \qquad (2)$$

With a target period of approximately 44 seconds and a duty cycle of 45.4% to allow for a response from the springs, the program was run and the desired PWM for testing with two SMA springs was obtained. Since one spring should remain off while the other contracts, a phase delay was utilized. Figure 24 shows the closed-loop program developed in SIMULINK to accomplish this control scheme.

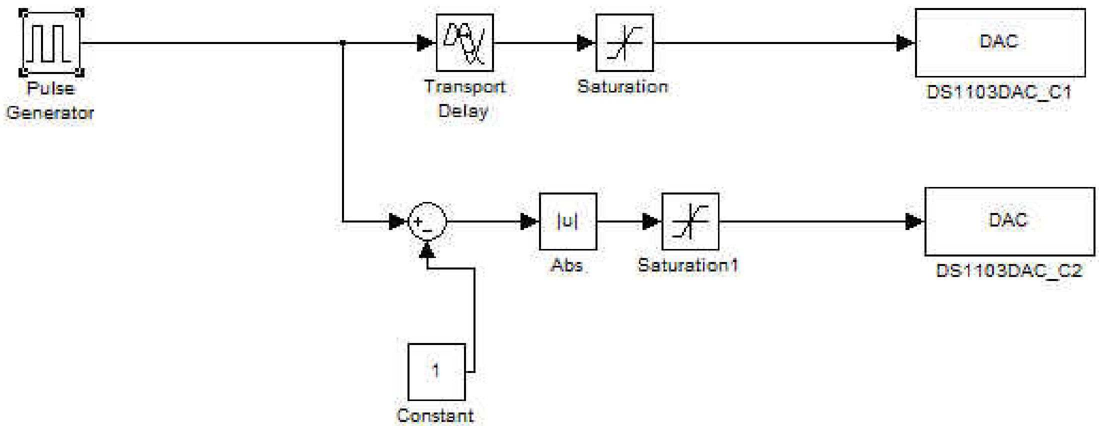


Figure 26 Open-loop block diagram developed in SIMULINK to test the circuit for the alternating contraction pattern.

The results of this test with the proposed period of 44 seconds were compared to observations made during manual testing. Sufficient contraction mechanism for the robot during the deformation process was not feasible. After adjusting the values again, a period of 84 seconds and duty cycle of 47.6% generated the desired time-based pulses with enough duration to allow stretch during cooling and full contraction during heating.

Despite the occurrence of contraction, response time had room for improvement. The supply voltage was increased to 3.5V and an improved response time was observed. The pulses were also shortened to avoid spring burnout. The phase delay represented cooling time, and the cooling was aided by the bias force that the elastic shell provided. With these considerations in mind, PWM was adjusted to deliver the expected performance from the springs as described in the following section.

dSPACE Testing Using PWM

A SIMULINK program was developed that utilized a period of 18 seconds and duty cycle of 33.3%. Once the program was built and uploaded to the Control Desk, experiments showed some deformation in the SMA springs. The figure below shows the physical test bed using two of the three springs.

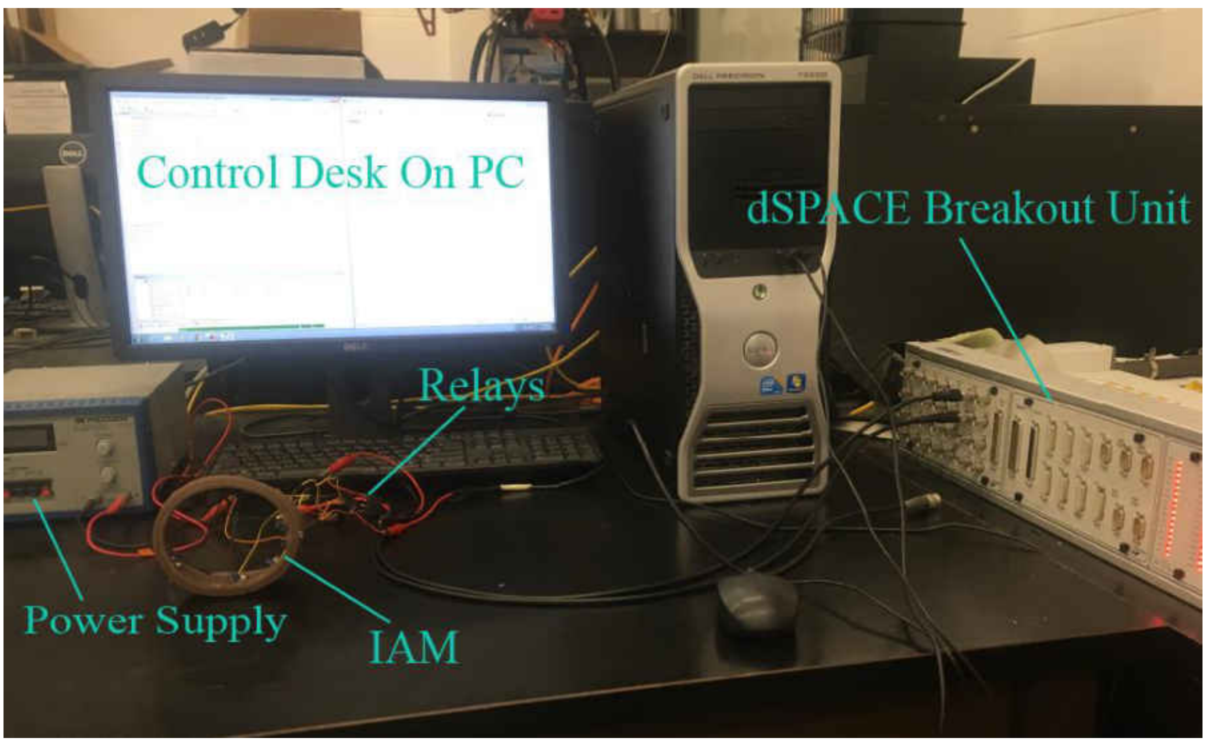


Figure 27 Test setup using dSPACE, prototype, and desktop computer. dSPACE Control Desk shows the output values for the saturation values to verify the switching voltage being applied to each relay at any time.

EXTERNAL ACTUATION METHOD (EAM)

The design described in the previous section challenged the previous concept implemented by Steffan, et al. by suggesting an intrinsic deformation mechanism as seen in nature would more sufficiently create a rolling circular robot. However, several complications were met with the IAM design. Thus, the author considered a different approach to the problem while still maintaining soft robotics concepts since literature has shown that these robotic systems produce successful microsystems. The external actuation concept illustrated in this chapter is an adaptation of the previous prototype built while maintaining the characteristics seen in soft robotics. Thus, in the EAM method, rigid linear actuators were replaced with soft actuators that worked in harmony with lightweight rigid components.

Details of Design Concept

This design required a circular core in which spokes would be configured radially such that 6 total legs would undulate from the center. Another requirement would be incorporating the springs such that the spokes would translate by means of spring contraction and relaxation. At rest, spokes would be in contact with the surface, however, upon contraction, a spoke may translate away from the surface, making the body unstable and shifting the center of gravity, thereby causing the robot to shift forward and regain stable contact with the surface via the next extended spoke. The undulation would be achieved by contracting these springs in sequence similar to the IAM design concept. Due to the springs and dimensions available, the springs were configured extrinsically, connecting the spokes to the inner core without obstructing spoke movement. The drawing below illustrates an initial design concept to meet these requirements.

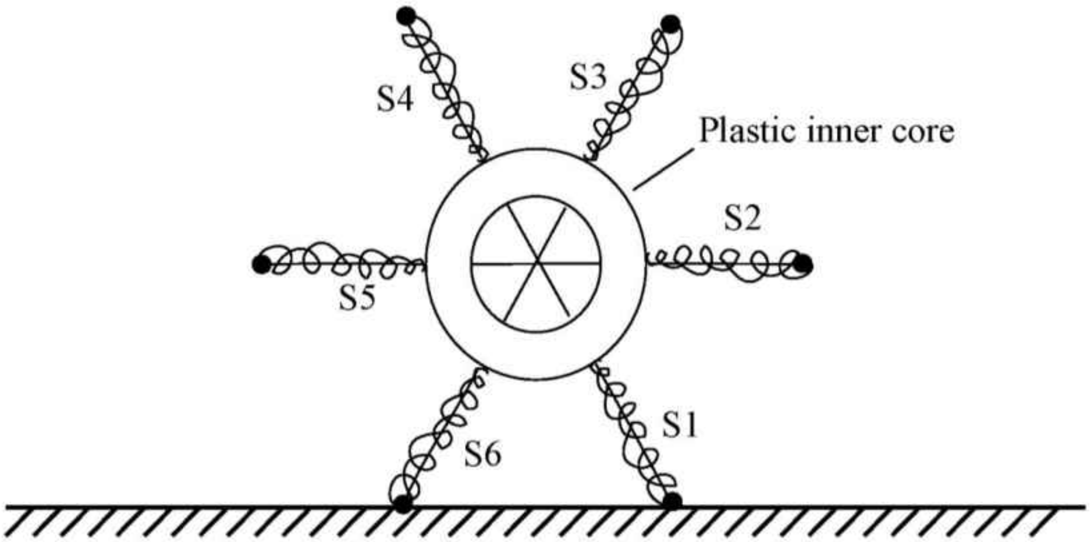


Figure 28 Soft robotics adaptation of previous work involving three diametric spokes and six SMA springs.

Drawings

Significant work was completed in the previous work in terms of the locomotive mechanism in an extrinsic actuation method, thus the conceptual basis behind the locomotive mechanics did not need further development. However, the challenge in this adaptation was to determine the SMA spring activation pattern that would generate the rolling motion desired. Figure 27 illustrates the proposed SMA actuation methodology.

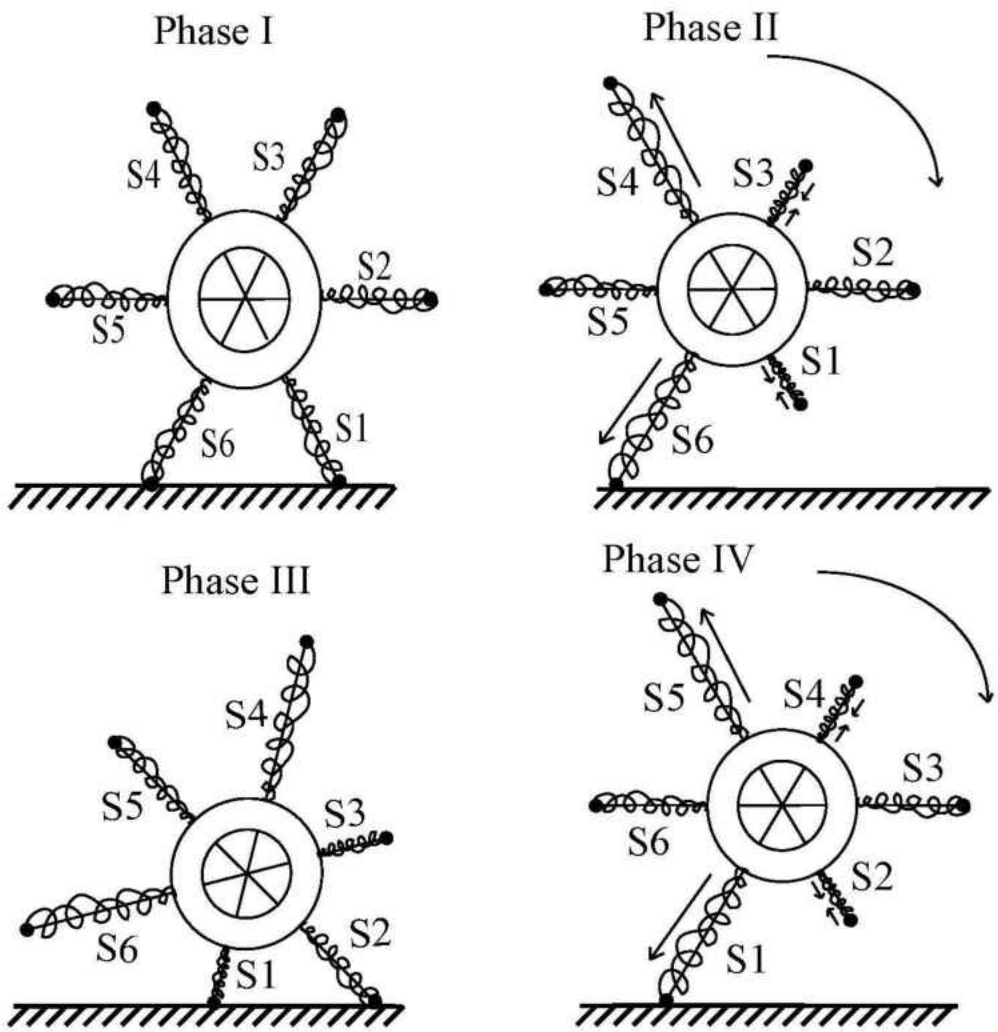


Figure 29 Proposed undulatory mechanism for soft robotics adaptation.

Given that S1 and S6 were in contact with the surface, S1 would contract to shorten the spoke length and tilt the core forward. The moment generated to "tumble" the robot such that S2 meets the surface would be due to S6's opposing spring. S3, upon activation, would contract thereby pushing the length of spoke toward the surface with a force that causes the robot to tumble forward. These steps would all occur during Phase I. In Phase II, heat would be removed from the active S1, thus making it S1', and applied to its bias SMA, S4. Meanwhile, S2 is activated. As S1' cools and stretches, the translation of that spoke pushes the robot forward so that S2 would contact the surface. This would repeat to produce the undulatory rolling motion as demonstrated by the previous work.

Prototyping

To prototype this design concept, a plastic spool, six SMA springs, and three 11-inch lengths of aluminum rods were used for assembly. After measuring the circumference of the core using a string and ruler, six equi-4spaced, but offset, holes were drilled through the core's surface using a $\frac{3}{8}$" drill bit. The spokes were spaced at 60º with respect to the other and the springs were implemented by placing the rods through the center of the springs. Ring terminals were used as physical attachments from each end of the springs to the most distal end of the spoke and contact with the circular core. Plastic spacers were used to prevent fouling of the ends of springs that passed through the center of the inner core. Lastly to secure the terminals to the distal end of each spoke, the rings were bent at a slight angle and passed over a cork stopper to ensure that those ends remained fixed during spring contraction.

Manual Testing

Before experimentation on the assembled prototype was performed, several manual tests were done on one spoke and spring. The test SMA was fixed on one end of the aluminum spoke, while the other end was free to translate. It should be noted that the rods were coated to prevent heat loss from the spring to the rod itself, which would ultimately lower the spring's ability to contract due to their resistive nature. The free end of the spring was stretched to the halfway point of the spoke, then voltage was applied across the spring.

This preliminary test showed that the spring was unable to contract due to frictional effects between the spring terminal and the surface of the spoke. This was due to the terminal itself, so it was replaced with a larger ring terminal. To further prevent opposing friction, the spoke was lubricated with engine oil to provide a friction-free surface for the free end of the spring to translate along. The spring was then re-tested and uninhibited translation was observed. However, for the assembly, the core itself would have to be in contact with the translating end of the spring to allow for spoke translation. Figure 28 shows how the spacer was utilized to overcome this challenge and allow for the “free-moving” terminal to remain fixed at the core without inhibiting the spoke’s translation.

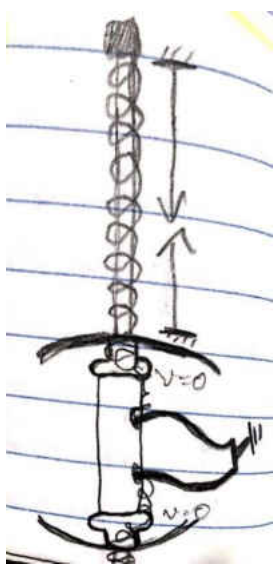


Figure 30 Assembly of SMA spring with diametric spoke and inner core.

Despite these improvements, the springs were still unable to contract. To overcome this final challenge, the springs were reconfigured such that each end of the springs were fixed to the distal ends of the spokes and the core, but the spoke did not pass through the center of the springs. Figure 29 shows the final prototype.

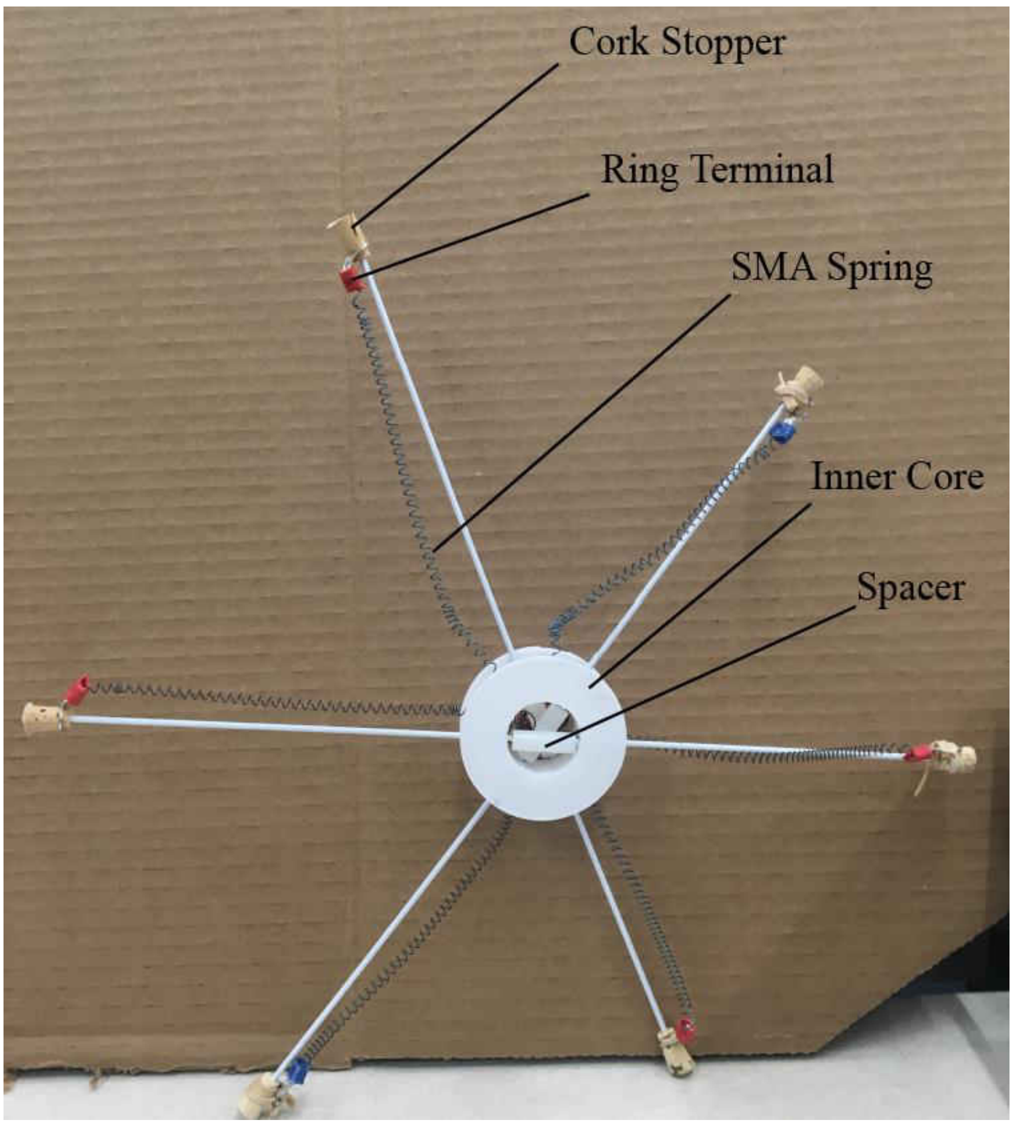


Figure 31 Assembled prototype for the EAM.

Manual testing was performed on this design as a proof of concept for a soft robotics adaptation of the EAM. Due to the dimensions of the components and the weight of the model itself, it was tested against a flat surface without the feet shown in Figure 30 to prove its ability to roll successfully. The resulting locomotion is shown in Appendix C.

CONCLUDING REMARKS

The work described in this thesis sought to conceptualize and propose two design methods for prototyping a circular robot that could roll or tumble forward continuously. The author reviewed the field of bioinspired robotics and SMA-actuated micro-robots before proposing the methodology explored and tested in this work. The objective was to simplify the previous robotic prototype developed and produce models that would be more feasible for applications in medicine, surveillance, and space exploration. After selecting an actuation method that would allow for these objectives to be met, two design concepts were proposed, prototyped, and experimented on. The following section discusses the results of this work.

Discussion

Conceptualization, fabrication, and testing of the first model demonstrated some body deformation. The first iteration of this design concept showed that the intrinsic actuators created surface deformations that generated a tumble, however, repeatability proved itself to be an issue. Therefore, the hypothesis for this design concept was disproved. Two separate experiments were then created and analyzed to justify this design concept. The first experiment occurred manually on a version of the IAM that included a wider shell and six parallel-actuated SMA springs. Repeatable rolling was accomplished; however, the author could not decisively conclude that this method proved the IAM hypothesis without implementing an automated control circuit. The future work section describes these next steps. Alternatively, an improved source of bias force or shell material and design could solve the recovery issue during the rolling process. Despite the difficulties seen during this phase, manual testing did show that the prototype was still able to demonstrate deformation mechanics and generate some locomotion.

The EAM, or soft robotic variant of the previous work, successfully showed that the previous model may easily be simplified and miniaturized to further meet requirements for various applications. The proposed design operated as conjectured since it adopted the concepts of the previous work, however, it demonstrated that a soft robotics adaptation was capable of achieving the same locomotion. Implementing a soft actuation method further mimicked that of mechanisms seen in nature and proved that SMA's are a viable option for miniaturization of the robot as envisioned by the previous work.

Although both designs were simplistic, operational, and cost-efficient, both concepts require more additional work before homing in on specifications to meet specific applications. The following section discusses the future work for both IAM and EAM.

Future Work

To further develop IAM into a model that fully meets the objectives previously mentioned, modifications on the shell design would need to be made to enable successful rolling locomotion without failure. The challenge for future generations of this design would be to find a silicone rubber with the optimal material properties that would allow for elastic deformation, but also would prevent the lateral warping as seen in the prototype fabricated in this thesis. If this fails to resolve the shell deformation issue, then adding rubber bands to oppose the force of the contracting SMA's might aid in the robot's recovery during the deformation process. Ultimately, if this still fails to meet the objective of the IAM design, increasing the width and the number of SMA actuators should prevent the warping issue.

Once this challenge is overcome, automation would be the next step. The author recommends that a framework for position control of SMA actuators is developed to prevent unintended actuation or lack of repeatability [17]. A position sensor would provide feedback on the spring's stroke. Furthermore, several variables would need to be considered when building this control system to produce reliable actuation. The author recognizes these variables to be heating and cooling time, stroke, supply voltage and current, and duty cycle per the PWM discussion in this paper. A recommendation would be to determine the type of control that would implement this feedback in a closed-loop system and tune these variables to encourage reliability of these actuators. Once this is complete, a C code may be generated then uploaded to a microprocessor for automation. Finally, the circuit would need to be configured onto the robot without adding too much weight or interfering with the physical deformation process. Longer term objectives would be to miniaturize the IAM for specific applications such as drug release systems. This can be accomplished by using smaller lengths of SMA material, biocompatible material for the shell, and developing a compartment for drug storage and a mechanism for release.

Next steps in EAM would be developing a control circuit that is capable of automating six SMA springs for locomotion. Furthermore, adding a position sensor to the control system to process stroke feedback from each actuator, much like recommendations for EAM, would enable the robot to operate reliably and autonomously. Miniaturization is also possible for the EAM design concept. With a decreased inner core and shorter spokes, using shorter lengths of an SMA spring would easily transform the design into a micro-system capable of generating rolling locomotion. Additionally, determining how to redesign the ends of each spoke to gain stability is recommended. Developing this aspect of the design would further enable the EAM to roll on its own and without support.

APPENDIX A: APPROVAL LETTER

UNIVERSITY OF CENTRAL FLORIDA
COLLEGE OF GRADUATE STUDIES

Thesis Approval

Students should obtain all signatures except that of the College of Graduate Studies Dean, who signs only after entire thesis or dissertation process has been completed. Only one copy should be delivered to the College of Graduate Studies in Millican Hall 230.

Student Name:	Lietsel Richardson	**PID:**	2844331
Title:	Conceptualization and Fabrication of a Bioinspired Mobile Robot Actuated by Shape Memory Alloy Springs		
Defense Date:	04/03/2019		
Academic Program:	Biomedical Engineering MS	**Degree:**	M.S.
Department:	Mechanical & Aerospace Engr	**College:**	Engineering & Computer Science

Release Option(s):	**Term:**	**Expiration Date:**
Release Option Public	Spring 2019	05/15/2019

It is recommended that this work be used in partial fulfillment of the requirements for the degree name above.

Committee Signatures

The members of the Committee have reviewed the results of "Review for Original Work" submission, participated in the defense, and approve the work named above. The Chair of the Committee approves the release options named above.

Name	Title	Signature
Tuhin Kumar Das	Chair	Tuhin Kr Das
Sudeshna Pal	Co-Chair	Sudeshna Pal
Helen Jingi Huang	Committee Member	[signature]

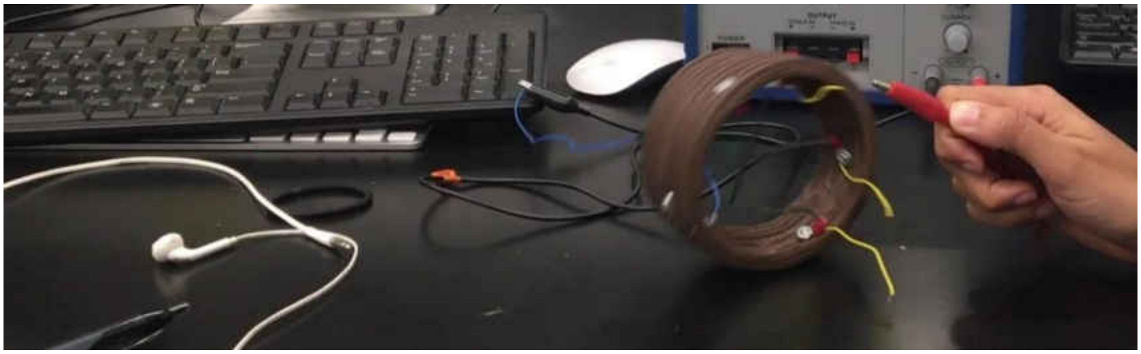
Program/College Signatures

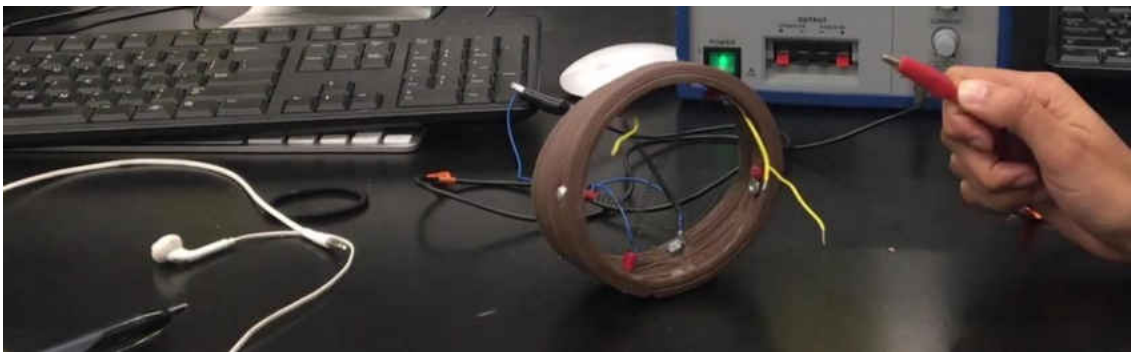
Name	Title	Signature
	Program Director	
	Chair/Director*	
	College Associate Dean*	
	College Dean	
Elizabeth Klonoff	Vice President for Research and Dean of the College of Graduate Studies	

The committee, the college, and the University of Central Florida are not liable for any use of the materials presented in this study.

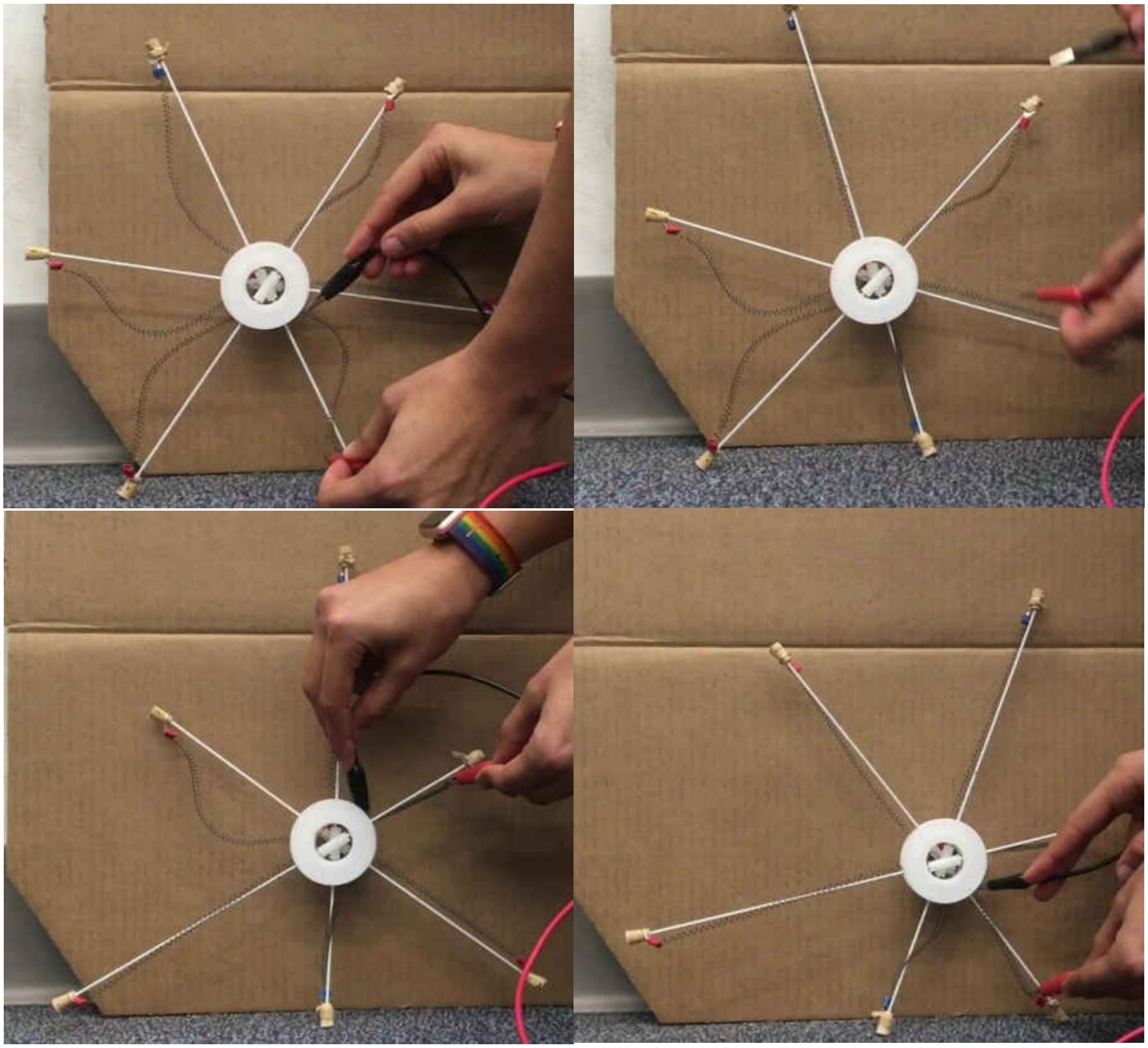
*If required by your college. The College of Graduate Studies requires the signatures of the Program Director and Dean of your college as well as the College of Graduate Studies Dean, whose signature will be obtained once this form is submitted.

APPENDIX B: IMAGES OF IAM LOCOMOTION





APPENDIX C: IMAGES OF EAM LOCOMOTION



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