Mobility of a Soft Conformable Multi-Limbed Robot Actuated by Shape Memory Alloy Wires

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Abstract—**Soft robots promise a number of advantages over their rigid counterparts, including the ability to conform to and manipulate arbitrary geometries, conjunction acceptance through contact absorption, and an increased range of motion through deformability. Increased robustness and resilience make soft robots an interesting mobility and manipulation platform for both on-orbit and extraterrestrial applications, where topology is unknown and/or varied with highly sensitive components and materials. There they can have both geometric mapping and manipulating applications. In this paper, a possible architecture for a mobile soft robot used for sensing its environment through locomotion over a 3D surface is proposed, and an individual limb prototype is built and tested in one-g environment. A multi-limb robot architecture is proposed where each limb has more than one SMA wire actuator, allowing for additional degrees of freedom freedom when multiple SMA wires are actuated in tandem. Shape memory alloys (SMAs) are chosen as possible actuators for their better suitability for space applications, instead of traditional fluidic and pneumatic systems, to eliminate risk of losing the consumable fluid on orbit. A single limb prototype is created that consists of the SMA wire actuators, a backbone spring-shaped structure to keep the SMAs under load, a protective silicone skin, and an electrical interface. Challenges inherent to working with SMAs in creating robust mechanical and electrical interfaces, as well as providing predictability in actuation direction and force, are addressed through the limb design, and a baseline characterization of the design is presented. Experiments done to characterize the limb's maximum displacement, load bearing ability, and longevity point to this being a promising design for further creating and testing a multi-limbed ambulating robot. A preliminary gait is discussed to show feasibility of locomotion with the achieved limb architecture and displacement.**

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1. Introduction

Mapping surroundings, gripping and manipulation of objects, and exploring extreme environments are all goals of robotic systems, and the robots' locomotion capability and characteristics are one of the essential elements determining their performance characteristics. For extraterrestrial applications, there is growing interest in exploring terrains like icy crevasses and lava tubes to seek out life and geological features of scientific or commercial interest [1], [2]. There is also a growing interest in being able to explore and perform tasks in a microgravity environment, such as for on-orbit servicing and manipulation, debris removal, and in space assembly and manufacturing [3], [4].

Traditionally, robotic platforms have been entirely or largely made of rigid materials, with well defined rigid limbs and bodies connected by motion components i.e. motors. However, soft robots have long been recognized for their possible advantages due to increased ability to conform to their environment and have less invasive interactions with it [5], [6], mimicking the versatility of their biological counterparts. They boast an increased range of motion, adaptability to the environment, and robustness. Hyperactuation, or greatly increased degrees of freedom freedom, and outstanding locomotion abilities of bioinspired soft robots are particularly promising for movement within challenging terrain, such as tightly constrained spaces, significant slope gradients, and submerged environments [5]. Significant work has been done in achieving locomotion with invertebrate robots [7], as well as ones that feature a collapsible internal skeleton [8], [9], but despite the notoriety that soft robots are gaining on Earth, largely for medical and wearable applications [9], [10], on-orbit and extraterrestrial applications still largely rely on traditional rigid architectures, even for their bioinspired designs [11]. They are prone to damage from entrapment and inelastic collisions due to being rigid [12]. Similarly, the nascent field of on-orbit robotic operations and assembly has been heavily relying on traditional robot arms in both proposed and already demonstrated missions [3], [4].

STARFISH (Soft Translating Autonomous Robot for In Space Handling) is a robot concept for a bioinspired soft compliant crawler capable of self locomotion while carrying a science payload. It consists of a soft central body that encases electronics and several limbs with individual internal skeletons, actuated by shape memory alloy wires (SMA's). Artist's depiction of the proposed robot is shown in Figure 1.

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Statement of Contribution

This paper presents a concept for a new type of a soft crawling robot that broadens locomotion capabilities of soft robots that use shape memory alloy wires. The main contributions are (1) a design study on possible limb architectures to achieve a significant range of motion in multiple axes. (2) A working limb prototype that achieved multi-axis actuation using a shape memory alloy multi-wire configuration and a semi rigid highly compliant structure on the inside on each limb. (3) A preliminary gait model showing feasibility of the chosen method of locomotion for the results achieved on the prototype.

Paper Organization

The following section (section 2) summarizes relevant work done to date in achieving locomotion of soft robots, focusing on shape memory alloy actuation, and discuss which elements were chosen to pursue further and why. Section 3 introduces STARFISH architecture proposed to date and an overview of the intended prototype. Section 4 discusses the details of the parameters considered for the limb design and the design details, and the design implementation on a single limb prototype as well as motion tests performed with it over time. Section 5 contains a proposed algorithm to achieve multi-limbed motion with the described limbs, followed by Conclusions regarding the feasibility of the chosen locomotion method and future work to be done.

Figure 1. **Artist depiction of STARFISH traversing rocky terrain**

2. Related Work

For STARFISH to achieve its potential and goals, it needs to have an implementation of at least the following subsystems: actuation, computation, power, and sensing. All of these subsystems need to be embedded in a soft material, and be as soft as possible themselves [5]. The goal is for the body to partake in computation using impedance matching, and thus have a form of ”mechanical intelligence”, considered one of the benefits of bio-inspired robots. In order to address inherent challenges of thinking about traversing unknown terrain, STARFISH was modeled as a gripper-manipulator when appropriate, drawing inspiration from other novel multilimbed robots [13].

The main two methods of soft robotic actuation to date are variable length artificial muscles or tendons (pulley-rope systems, tensegrities, or shape memory allow wires) [5] and fluidics (pneumatic and/or fluidic chambers that pressurize and depressurize to vary in size) [7]. Fluid-based actuators, including air, have been very successful in a variety of grasping and locomoting scenarios, such as the octopus tentacle and the multigait robot (Figures 2, 3). They use variable stiffness and controlled discretized rigidization to achieve contractions of the artificial muscles [6].

The soft robots of this type can be separated into the ones that are entirely soft and rely on separation of internal chambers built into the soft structure to create deformation, such as demonstrated in the Figure 2 [7], [14], [15], and ones with partially rigid internal structures (Figure 3) [9], [8]. The internal structures help with controlling directionality of the contractions, especially when the rest of the limb is made of material with homogeneous properties, which is more common for robots actuated by tendons.

Figure 2. **Pneumatic multigait robot, [7]**

Figure 3. **Fluidic-actuated artificial octopus tentacle, [16]**

In order to ensure compatibility with space environments which are often devoid of an atmosphere, shape memory alloy wires were selected as STARFISH actuators rather than relying on a fluid which would be a consumable. Shape memory alloys can contract as much as 4 percent when subjected to thermal stress, and resume their original length upon cooling down due to a phase transition [17]. They have been used for one-directional motion, either contracting and expanding the distance between rigidly attached robot legs [18] or imitating peristalsis of a worm [19], [20]. To introduce directionality to SMA-based actuation, a structure can be embedded in the soft material of the limb to create variable stiffness [8], which will enable bending motion in addition to contracting and expanding motion. Since these structures need to be omnidirectionally bendable, origami is frequently turned to as a way to fabricate such a structure [8], [9], [21], with a general principle shown in Figure 4. A similar internal structure was chosen for STARFISH, since it allows for extrapolation from one limb to a multilimb gait. To decrease complexity, a design alternate to origami-based fabrication was considered for creating the structure.

As actuators, SMAs pose a variety of challenges related to speed of actuation, repeatability of displacement, the need to preload the actuators, and the inherent single dimension directionality of each actuator, requiring increased inner structure complexity. Some of these are investigated on a single-limb prototype implementation and discussed in this paper.

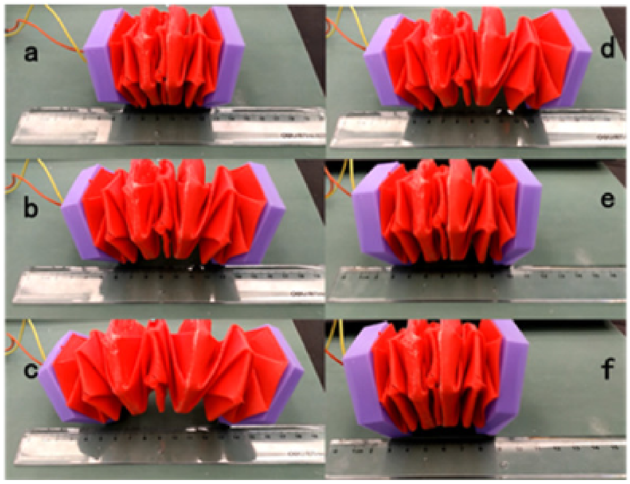

Figure 4. Principle of an origami based internal structure for a soft robotic limb [21]

3. STARFISH CONCEPT

Overview

STARFISH is presently conceptualized as a 4-limbed robot, although the number of limbs can be changed without affecting the robot architecture. The body is meant to carry a centralized controller that commands the actuators in each limb, and eventually a sensor used to demonstrate an environment mapping application. The limbs have built-in actuators that allow them to bend in multiple directions to achieve an ambling gait. The actuators are wired directly to the controller carried by the body. For the prototype, the controller will be capable of simple bang-bang control scheme, and the sequence of commands will be hardcoded, with a possibility of implementing real time control and eventually moving to a distributed control model per individual limb. The current STARFISH concept is illustrated in Figure 5.

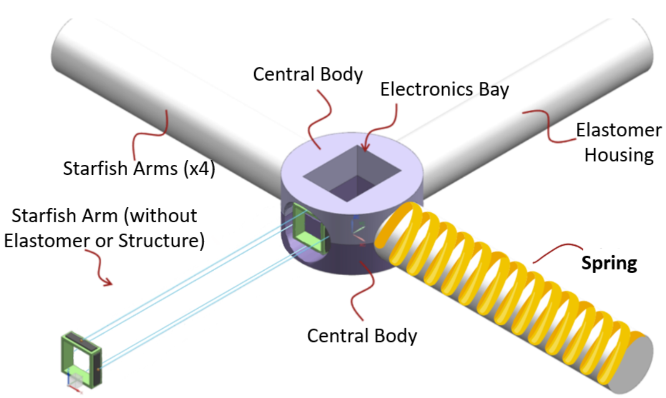

Figure 5. STARFISH overview, limbs are presented in different views

Limb Design

Limb design has been the main focus of this work. Each limb consists of the following components: SMA wires for actuation, an internal structure that provides directionality and keeps the SMA wires in necessary tension, attachment pieces for the physical and electrical interfacing of the SMA wire, and the soft silicone body. Each of those is described in more detail below.

The internal semi-rigid structure is comprised of a double helix spring. A double helix design was chosen for two reasons. Geometrically, it needs to allow for upward and downward bending, lateral bending, compression, and torsion. It operates similarly to the previously used origami-based structures [9], [8] but allows for easier customization and faster manufacturing, enabling the spring design parameters to be optimised through prototyping. Secondly, in order for the SMA wires to actuate repeatably, they need to be in tension at the time of actuation [22]. Multi-wire configurations need to have all the wires in identical tension to each other. Using a spring structure allows for the equal tensioning to be done passively, without the need for additional tensioning mechanisms.

Spring variables considered were free length, spring diameter, coil diameter, and pitch, which were chosen such that the spring can provide force of at least 2N and not greater than 5N, and leave enough space for the SMA wires to be routed inside.

SMA wires are routed on the inside of the spring. Each limb has 4 wires offset by 90 degrees to increase mobility. When an SMA wire is heated via applying voltage it compresses causing the spring to change shape. Four wires are used to increase mobility since SMA wires can only have two lengths due to their nature. The placement of the SMAs relative to the spring are shown in Figure 6. To avoid tangling and inadvertent shorting, guide holes are added on the inside of the spring that the wires are fed through (Figure 7).

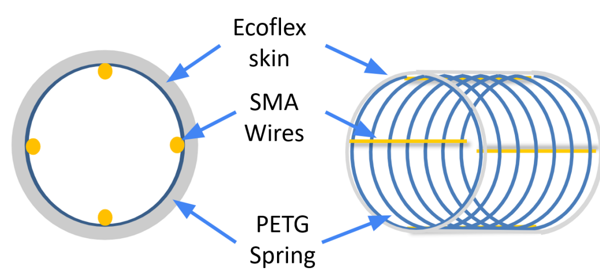

Figure 6. Limb cross section

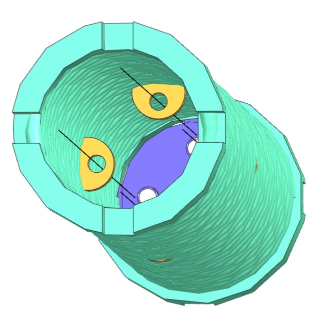

Figure 7. CAD showing guide holes for SMA wires

Creating physical and electrical connection for SMA wires is challenging due to their size and the need to keep them under tension [22]. Due to difficulty of manually cutting the SMA wires to exact length and identical manual installation, their attachment had to allow post-installation length adjustment. Any difference in length between the four SMA wires would have resulted in the spring being prematurely bent. Ultimately, two different attachment methods were implemented on different ends on the spring, one for fixed wire attachment and one that allows length fine tuning. For the fixed end, brass crimps were fabricated and used to feed the SMA wire through a few times to create a loop so that they could not be pulled out. An exposed end of a jumper wire is inserted on the other side of the crimp, and both the jumper wire and the SMA wire are secured inside by flattening the crimp (Figure 8). This attachment was successfully tested for being able to resist a pulling force of 20N. For the variable length end, a screw attachment was used. The SMA wire was looped around under a head of a screw that could be loosened and tightened while adjusting the tension of the SMA wire, and tightened for the last time when the correct length and tension were reached (Figure 9). Attachment pieces were made to interface with the spring and the crimps, completing the installation of the SMA wires in the limb.

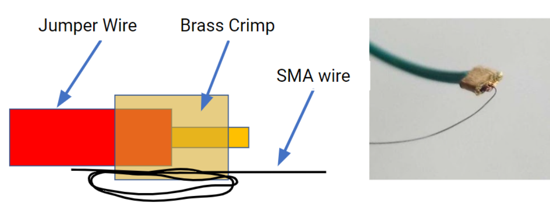

Figure 8. Fixed SMA wire attachment. Left: Diagram. Right: Prototype

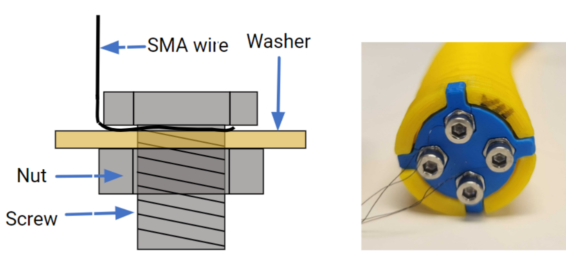

Figure 9. Fixed SMA wire attachment. Left: Diagram. Right: Prototype

In order to ensure repeatable assembly, a jig was designed and used that compresses the spring as the limb is being assembled as to not interfere with the assembly process. The wires are installed and secured while the limb is compressed, and then the limb is released. As it elongates, the wires become taught, and it is evident if adjustments are necessary (if some wires are shorter than others, the limb is prematurely flexed to one side). The length of the wires is fine tuned to achieve a straight spring, and then they are tightened from the variable end.

The outside of the limb is covered with soft EcoFlex silicone. The design of the entire assembly is shown in Figure 10, except for the skin that's applied over the top of the spring.

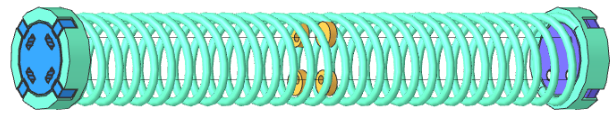

Figure 10. CAD of a limb design, silicone skin not shown

Gecko Adhesion

In order for STARFISH to exert enough force to anchor some limbs while moving others forward, introducing an adhesive at the end of each limb was considered. This adhesive would have to not rely on chemical reactions and be effective in vacuum conditions. The two most promising technologies are electrostatic adhesives and gecko adhesion. Electrostatic adhesion is operational in a vacuum and doesn't require chemical bonds or pre-stressing force [23]. However, this technology still has limitations including its relatively low and highly dependent separation gap between the adhesive and target substrate.

The stronger candidate for adhering to outside objects is gecko adhesion. Gecko adhesives consist of asymmetric structures that confirm to the target surface and produce adhesion when loaded in a specific direction. The ability of the adhesive to respond to loading allows for its control in an ON/OFF manner and improves surface conformance on a microscopic scale. The joint USC/JPL REACCH project [24] uses a directional dry adhesive developed at JPL that consists of triangular microblocks about 20 μm wide at their base, 60 - 70 μm high, and about 200 μm long.

The Jet Propulsion Laboratory (JPL) developed a hybrid combination of electrostatic and gecko adhesion to increase the shear force. The electrostatic adhesive provides initial clamping to the surface. Then, the gecko adhesive bristles contact the substrate once loaded, reducing the distance between the substrate and the EA, which then increases its effectiveness. It is the combination of these two types of adhesion that is intended to be used in the STARFISH project.

4. Implementation on Individual Limb Prototype

SMA wire selection

For actuation, Flexinol SMA wires of 0.05 mm, 0.1 mm, and 0.15 mm diameter were considered. Their specifications are summarized in table 1. 0.1 mm thickness was chosen for ease of handling (anything smaller was too thin) and relatively little required current. After testing, they were experimentally found to generate the greatest force of 10 Newtons when 300mA was being supplied.

Table 1. SMA wire summary

Characteristic	0.05 mm	0.1 mm	0.15 mm
Mass moved, hot (g)	36	143	321
Mass moved, cold (g)	14	57	128
Current (mA)	85	200	410
Cooling time (s)	0.3	0.6	1.7

Limb Manufacturing and Assembly

PETG with 98A shore hardness was selected as the 3D printing filament for its flexibility, which allows the spring to deform and return to initial state without premature brittle failure. A few prototypes of varying length, diameter, and pitch were made and tested for maximum generated force and deflection ability. Ecoflex 00-50 was used for the skin (Figure 11).

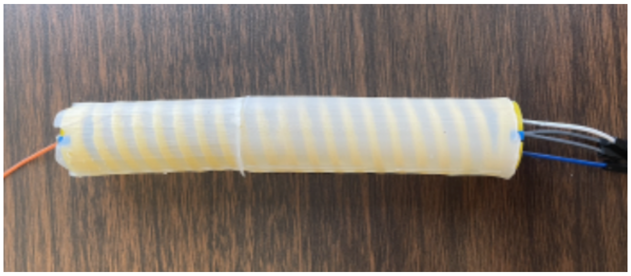

Figure 11. Ecoflex skin stretched over the spring skeleton

Electrical Schematic

The schematic for the circuit that was used to power and control one individual limb is shown in Figure 12. The existing implementation used an Arduino Mega as the primary controller, although a RasPi nano is a strong candidate for future iterations as it has enough channels to control at least four SMA wires and is more compact and lightweight. It uses a current sensor as a preliminary proposed way to sense its surroundings.

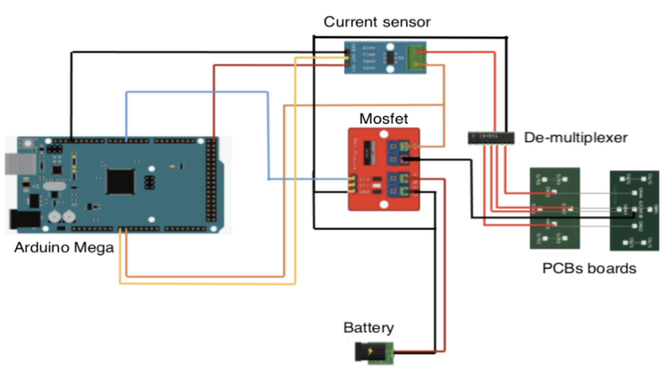

Figure 12. Circuit diagram of one limb with 4 SMA wires

Prototype Performance

Following the fabrication and assembly of the prototype limbs, their actuation properties were tested. The limb was connected to a power sources and secured at one end, and actuated to move left, right, upwards, and downwards. Displacement was measured in centimeters with a caliper and in degrees, overlaying the initially straight limb over a circular print out of a circle, with one end secured at the origin. The displacement of the tip of the flexed limb was measured in centimeters for actuation to the left, right, top, and bottom directions, and but number of degrees of degrees it moved was recorded only for planar movement. The resulting maximum achieved linear and angular displacements are recorded in the table 2. A separate test was done to investigate any changes in performance over time.

Table 2. Limb displacement summary

Direction	cm	degrees
Right	2.5	33
Left	2.2	29
Top	2.1	n/a
Bottom	0.8	n/a

A series of displacement tests were done over the course of 20 days to track the lifecycle of the SMA wires and the structure. The limb was actuated once a day, and the resulting displacement was recorded. The results show a degradation in all directions, with worst degradation of 38 percent being experienced by lateral displacement (left and right), as shown in Figures 13 and 14.

The degradation in performance exceeded the expectations of SMA lifecycle and is hypothesized to be related to design choices in securing the SMA wires. It is possible that due to imperfections in their attachment, their tension decreases over time as the bolts loosen themselves, leading to decreased performance. A more robust attachment method needs to be developed.

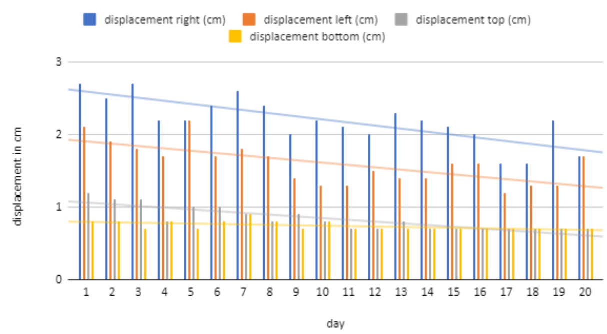

Figure 13. Change in max displacement over time, cm

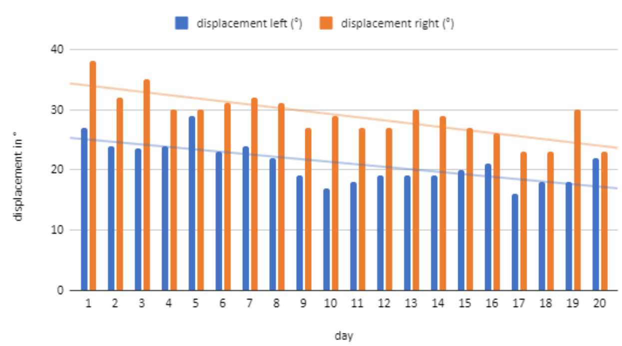

Figure 14. Change in max displacement over time, deg

It needs to be noted that left and right displacement are not identical in the chart included, although based on the design they should be. A difference of up to 0.75 cm and 10 degrees is attributed to the imperfection in assembling the prototype. The included SMA wires were not set to the identical length, which resulted in them experiencing different tension, which in turn caused different maximum displacement. It further shows the importance of a robust assembly method that minimizes manual processes. It is also worth noting that the displacement difference between the left and the right side remained relatively constant as they both changed over time.

Lastly, the maximum produced forces were measured parallel and perpendicular to the direction of actuation. To measure forces produced during the compression of the suspended limb, at first the spring was attached to a test stand with a known mass was attached to the bottom of it, and the displacement of the mass was measured. These results were verified by using a Vernier scale, attached directly to a horizontally placed limb. To measure the force created from actuating the limb sideways, a Vernier scale was connected to one end of the spring perpendicular to it, and gave the direct measurement during actuation. The setup is shown in Figure 15, and the averaged results are summarized in table 3.

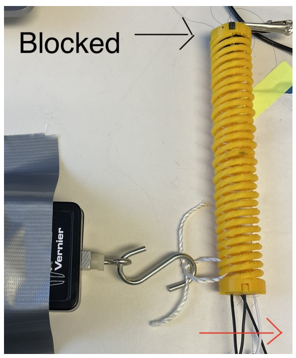

Figure 15. **Displacement measurement setup**

Table 3. **Forces generated**

Direction	Force [N]
Force produced when bending sideways	0.1
Force produced when compressing	4.9

5. Path Planning

The distance the limb can move, or the total displacement of its end effector, is one of the main factors that affect possible locomotion sequences. For STARFISH, that distance is determined by the length of the limb and strength of actuation. The prototype of the limb, when secured at one end and actuated, demonstration motion of the free end of up to 2.5 cm, and 30 degrees bend of the entire limb. These numbers were used as constraints to create possible locomotion trajectories. The robot was looked at as a planar robot moving in 2D, and assumed to have 3 degrees of freedom: translation in x and y, and rotation of the body, all achieved by actuation of the limbs and engaging-disengaging of the gecko adhesives.

Two types of trajectories were considered for STARFISH's locomotion in 2D: 1. Straight or linear, when the robot rotates its body in place to achieve desired orientation, and then translates to the endgoal in a straight line (Figure 16); and 2. Curvilinear, where the robot turns its body and translates at the same time. In the latter case, the motion can approximated as tracing a curve of a circle, Figure 5. This method is hypothesized to be more representative of the motion feasible for the prototype once a 4-limb version is created and integrated with gecko adhesives.

In both cases, the actuated limb or limbs is assumed to move a controllable angle γ relative to its original orientation, and

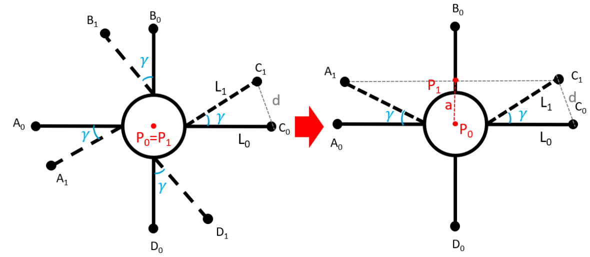

Figure 16. **Linear Motion Schematic**

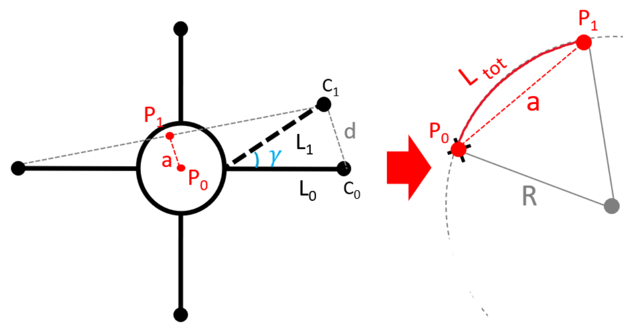

Figure 17. **Curvilinear Motion Schematic**

its initial length L_0 is contracted to the new length L_1. The end effector of the actuated limb(s) moves distance d, and engaging the gecko adhesives results in the body translating a distance d from P_0 to P_1. The trajectory defines a curve corresponding to a succession of small straight lines of identical a, which can be visualized as a part of an arc of circle with radius R. To ensure realism, γ was set to 30 degrees, and d was set to 2.5 cm, which were the values gotten experimentally when making visualizations described below.

Linear Trajectory

Linear trajectory as STARFISH would track it is shown in Figure 18. For simplicity, it assumes the body can rotate first to its desired orientation in the considered 2 dimensions, which is something the physical model is not anticipated to be able to do. Position 1 indicates the starting position. Position 2 shows all arms being activated and rotated n degrees, to achieve the desired body orientation. Position 3 shows the right limb rotates towards the front around 30 degrees. Position 4 shows the front limb moving to the left so it is once again offset to the previous limb by n degrees. Position 5 shows the left limb moving towards the rear limb. Position 6 shows the back limb rotating to the right returning all limbs to the original 90 degrees offset from each other. Comparing the first and last image in the sequence shows that STARFISH rotated a total of n degrees.

Curvilinear Trajectory

Figure 19 demonstrates a possible curvilinear trajectory for STARFISH, which no longer assumes the body can achieve the desired rotation in one step.

Position 1 shows the initial position for STARFISH. Position 2 shows the front left and back left limbs being raised in the pitch direction indicated in orange. Position 3 shows the same two limbs moving backwards in the yaw direction indicated in

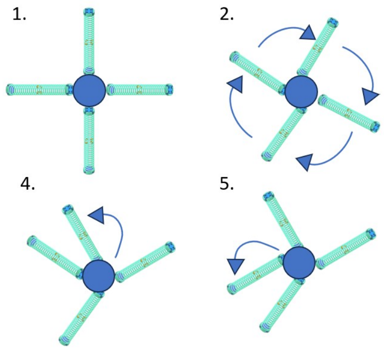

Figure 18. **Linear Sequence**

blue. The front right limb is also raised in the pitch direction. Position 4 shows the upper right limb is moved back so its pitch angle is returned to 0 degrees. Position 5 and Position 6 show the bottom right and top left limbs returning to the original pitch position as well.

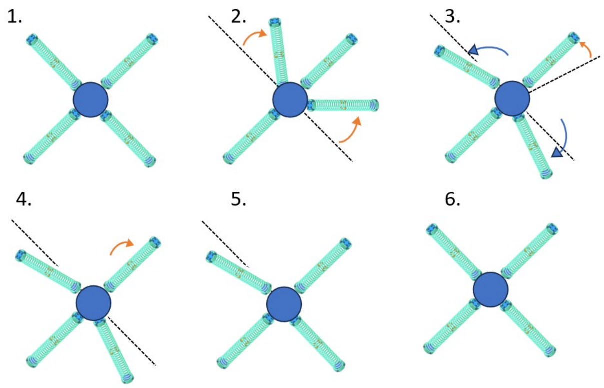

Figure 19. **Curvilinear Sequence**

6. Conclusions

Summary

The paper proposed a novel soft robot capable of crawling over challenging terrain. The proposed architecture included an overview of mechanical, electrical, and software systems that would enable the robot to locomote. A shape memory alloy based design of limb actuation is proposed and validated through a single limb prototype. A prototype consists of a helical limb structure that allows for omnidirectional bending, 4 shape memory alloy wires that allow multi-axial actuation, and the components for their electrical and mechanical integration. The structure keeps the SMA wires in tension and provides multiple axes in which the limb can bend. The prototype showed maximum deflection of around 30 degrees, which is promising for being able to walk. Lifetime tests were done on the prototype to characterize any changes in performance from regular actuation. A preliminary gait design is discussed.

Lessons Learned

Initial demonstrations of the concept on hardware showed promise. The prototypes were viable to manufacture, assemble, and actuate. They demonstrated enough movement to design a gait that relies on that displacement, and generated enough force for a locomoting prototype to be feasible. Assembly with SMA's proved challenging due to their small diameter, limited ways to affix them both mechanically and electrically, and the need for consistent tension applied to them. Once assembled, the prototypes showed more performance degradation than anticipated, possibly due to loss of tension in the SMA wire, necessitating improvements be made in the SMA assembly process. The displacement results also had significant variance, which will need to be addressed before creating a more robust prototype.

Future Work

Future work is planned to continue improving performance of SMA actuators, mostly their reliability, to allow for more repeatable limb displacement necessary for a rigorous trajectory design. However, since SMA's inherently do not have high reliability, the controller needs to be designed to operate with a relatively high velocity and position tracking error. Mechanically, more robust mechanical and electrical connections of the actuators need to be created for a portable robot to be created, the central body needs to be designed, and gecko adhesives need to be integrated into the design. Upon creation of the multi-limb robot, its main goals will be achieving locomotion on terrain with high slopes and slippery surface, such as sand or dust.

Acknowledgments

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