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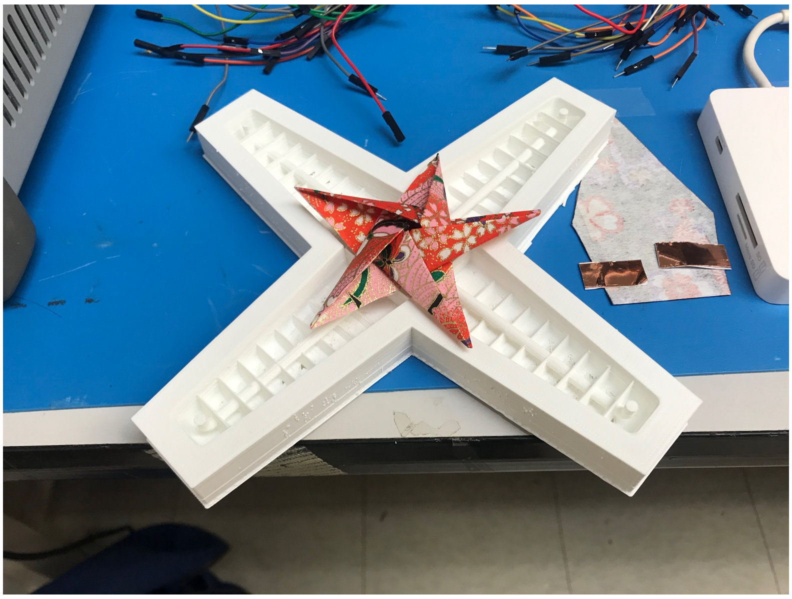
# STARFISH:
# Soft Translatable Advanced Robot for In-Space Handling



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**Abstract**

With the advent of on orbit servicing, the ability to build larger structures in space presents not only unique opportunities, but challenges as well. One of which is being able to constantly evaluate and supervise the platform assembly process and inspect resulting non-linear assemblies of the component elements e.g. mechanical, electronic, etc. On Earth space systems quality assurance of joints, assemblies, material, etc. is easily achieved through direct human validation prior to launch. The space element then goes through environmental testing to validate the system will hold up under the normal launch stress. Assembling elements on orbit does not yet have that same quality assurance verification and validation process. An assembled space platform then would benefit greatly from a ubiquitous, highly compliant, and flexible system that would be able to conduct the same if not similar inspections that provide validation of assembly. Soft robotics is a promising avenue of robotics research that could be applied to the validation of space operations. Soft robots developed as of now have exhibited their working functionality in water or on land, actuated pneumatically, using electroactive polymers, or cables. Most soft robotics research with regards to space applications is relatively new.

The University of Southern California's Space Engineering Research Center (SERC) is in the process of developing an actinomorphic-inspired robot merging soft materials, robotics, and electro or gecko-adhesion technology that is fully compliant and whose unique design allows it to walk, crawl, and round corners in space. The Soft Translatable Advanced Robot for in Space Handling, or STARFISH, robot is meant to be a self powered maneuverable inspection soft robot that can move around any space object and through internal sensors enable "inspection" of the specific elements. The idea is to deploy STARFISH sensors on an assembly that is occuring in space to constantly provide that validation and verification of quality of interconnections without having to do a full set of environmental tests, which is typical on Earth before launch.

Currently a working prototype using electro or gecko-adhesion tiles on the end of tentacles of the STARFISH are being tested at the SERC and the initial results of the investigation and testing are presented in this paper.

**Background**

As the advent of on orbit servicing comes of age, the ability to build larger, launchable structures in space presents unique opportunities and challenges. One of the challenges is constantly evaluating and supervising the assembly process by the various spacecraft that may be used, and inspecting resulting non-linear assemblies of various structural/electronic/manipulation elements. Whereas terrestrial construction has vantage points for human and robotic validation of joints, assemblies, connections, and quality of materials used in the process, the aspect of quality assurance that comes from “in person” inspection may not always be possible in space.

The team at SERC considered a number of potential methods to do verification and validation or inspection of non-linear constantly evolving assemblies in space. Some different methods included stand-off inspection vehicles end, effector sensors on a robotic arm, enmeshed structural sensors that transmit their own “connection” information, etc. Each has benefits and drawbacks for complexity, mass, and insertion into the “assembly environment”. STARFISH came about as an extension of a past research project at SERC called REACCH, which began to explore how to make docking and grasping easier without pre-determined interfaces. REACCH was a bio-inspired project to create a simple, easily deployable, smart, low mass and cost mechanism that replaces the need for very high cost and risk contact docking, to enable capture of any object, cooperative and/or non-cooperative, in space. REACCH utilizes low power high grip Electro-Adhesive/Gecko (EA/G) adhesion technology coupled with elastic substrates for ubiquitous geometric compliant grasping. Historically, capture is executed through pre-defined and mechanically fixed controlled contact methods or via uncontrolled methods such as nets. REACCH would be the first technology to service satellites without the use of a pre-existing docking interface through a dynamic, flexible grip.

Thus, having a ubiquitous, highly compliant and flexible system or element that can be deployed on an assembly in orbit, that is cheap to make and operate and can run entirely on solar power could be a solution for on-orbit validations. STARFISH takes the REACCH concept even further in that it incorporates existing concepts of soft robotics with Electro/Gecko-adhesion technology to create a “walking” inspection robot that is fully compliant, and that survives in space. STARFISH is also bio-inspired as it looks and operates similarly to an earth-based animal, in that with unique design it can “walk”, “crawl”, “round corners”, and “grow or shrink" as needed to inspect any type of structure on orbit. Whereas REACCH still required its “tentacles” to have structure to “grip”, STARFISH is attempting to increase compliance with on-demand rigidity through the use of shape memory alloy metals. Figure 1 shows the concept of STARFISH.

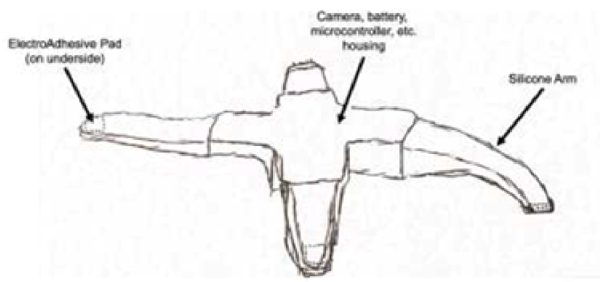


Figure 1: STARFISH Concept.

The advent of soft robotics offers a unique method to transfer the load path required for translation of an object, or grasp over a surface area to minimize potential damage and maximize “hold”. The concept of soft robotics is highly varied and rich. Figure 2 shows some examples of concepts that have both terrestrial and space application focus.

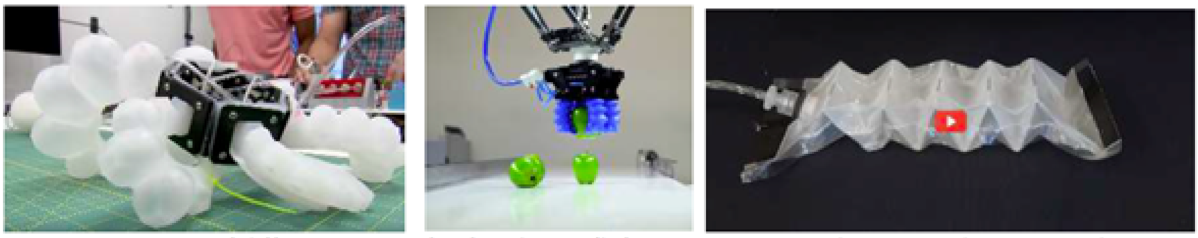

Figure 2: Depiction of different types of Soft Robotics (left image NASA Langley Research Center makerspace robots, middle image MASS Technology Leadership Council, right image Wyss Institute at Harvard University and MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) soft robotic artificial muscle concept).

From a research perspective, the challenge is how to maximize the "compliance vs. control" trade space to allow a "walking" robot to move over non-linear geometries at will. One of the challenges the team is investigating is determining the valid metrics for "compliance" and "control", that allows analogous comparison between various concepts and STARFISH. Another key challenge to a walking robot in space is maintaining grip or contact with the surface. This will be also looked at and discussed in the paper.

## Introduction

### 1.1 Project Goals

The premise behind STARFISH is the ability of a mobile soft robot that can be adaptable to traverse the exterior of a spacecraft for the purpose of inspection. The project goals are to design and create a prototype, evaluate its characteristics to crawl and/or walk in zero-G, look at integration of various inspection methodologies, and investigate and design the power, communications, locomotion constructs required to operate in space. The team focused on some key elements to start with, including the design of a suitable locomotion methodology that can also stay “connected” to the host platform in space as well as the design of the “body” that the locomotion elements e.g. “limbs” and actuation skeleton, are connected to for power, other electronics and control.

Our goal is to explore applications of shape memory alloy (SMA) operated soft robotics in the space environment. This “walking” robot would combine SMA and soft robotic technology with the understanding that it would need to withstand the harsh space environment. Our team is attempting to design and create a prototype with some level of autonomy, evaluate its ability to “walk” in zero-G, design inspection methodologies, and investigate operations capabilities.

Design and Models

## 2.1 Locomotion Methodology

The initial direction of our research was to understand the locomotion gait and the potential limitations or constraints that may place on the development of our physical prototype. A preliminary vector analysis was done to assess what types of forces may be imposed in both lateral and angular movement of a multi-tentacle walking robot. Figure 2.1 shows some of the first results. .

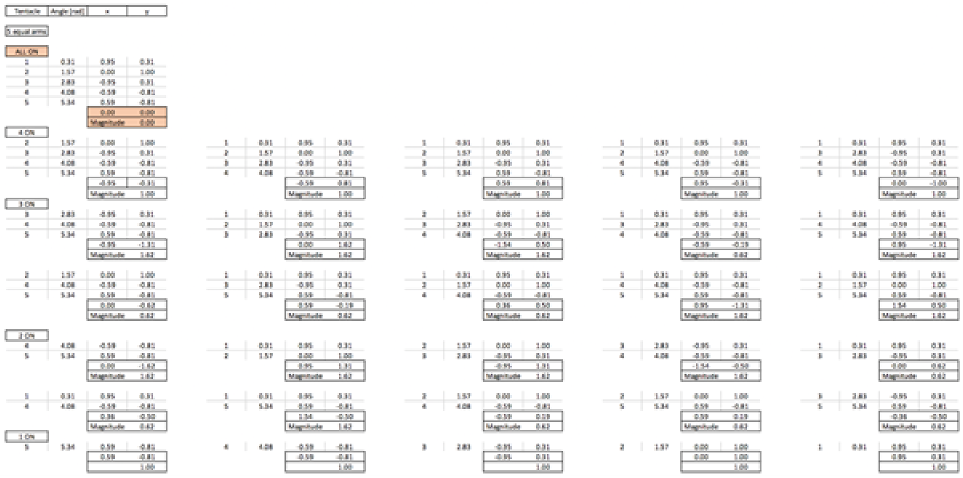

Figure 2.1: Early vector analysis for a 5-limbed body geometry showing the resulting force for any combination of active limbs.

Assuming each "limb" can produce a force of magnitude 1 in its respective direction, an angle was chosen for each limb to create a certain geometry. Then, the net force on the entire body and its direction were calculated for every combination of "on" state limbs. Figure 2.1 shows the vector analysis of a 5-legged geometry with equally spaced limbs. The same procedure was done for varying amounts of limbs and different arrangements of angles.

Here, a bit more detail was uncovered as to how a "limbed element" can maintain contact on a surface in space, where we assumed that to maintain contact in 3 dimensions at least 3 points of contact have to be made at all times. Once some initial analysis was created, our team then investigated existing methods for moving or manipulating soft robotics. The common practice on Earth is a fluidic transfer using either air or a liquid. This process involves pumping the fluid into specific channels of the soft device to create muscle-like movement [3]. With this pneumatic method, soft bodies can be easily bent and are very flexible[4].

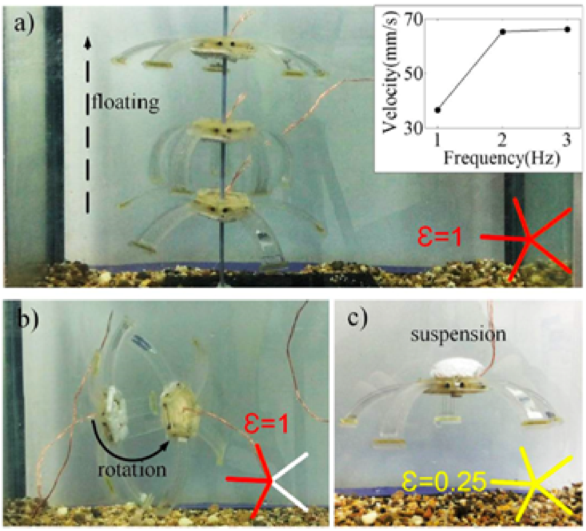


Figure 2.2: Soft robot, actuated by SMA wires, floating, suspending, and rotating underwater.

While demonstrated successfully, it was felt that for operations in space having a potential consumable that could escape from a potential failure seemed to present risks. Thus, our team investigated the use of shape memory alloy (or SMA) methods. Early soft robotics research has shown significant promise in this methodology in an underwater environment reference here. Figure 2.2 shows their instantiation using SMA into a very similar geometric move-able soft robot device. Considering that the SMA wires would only need electrical power, our team chose to pursue this as our initial locomotion methodology [5]. We looked at a combination of SMA wires (arranged bidirectionally), springs, conductive polymer hydrogels, and dielectric elastomers to create the locomotion prototype system. Considering that the SMA wires would only need electrical power, our team chose to pursue SMAs as our initial locomotion methodology.

## 2.2 Locomotion - Gait of a starfish

### 2.2.1 Locomotive Pseudo Code

We have developed an initial pseudo code that will be the outline for how we control the movement of the STARFISH robot through software. The code follows the structure of a microcontroller using one main infinite "while" loop. The algorithm will follow the design of a finite state machine, moving different legs depending on the desired direction.

```
Psuedocode:

Make each leg a new object (in code)

Start with assumption that all legs are down on surface

setup(){
    create arms (arm1, arm2, arm3, ...) (assume that code is the same for each);
}

loop(we want it to move){
    input direction
    based on direction choose which arm to move
    int x = 0
    while(x = 0){
        x = armmove(arm# based on direction)
        arm#++ % # of arms
    }
    maybe want some error checking (say if something isnt connected)
}


int armmove(arm#){
    check if all other arms are connected
    if(not){
        return back to the loop with 1
    }
    lift arm up
    move arm forward
    put arm down
    if(arm is not connected to ground){
        check if there is somewhere close to connect to
        if(not){
            put back where it started
            return to main loop with 1
        }
    }
    if(hits a wall/ other object){
        figure out where to put arm based on angle (not sure about this part)
    }
    return 0
}
```

Figure 2.3: Preliminary locomotive pseudocode.

### 2.2.2 Second Vector Analysis

A second vector analysis was carried out on MATLAB. The goal is to be able to determine how the STARFISH will behave quantitatively for a desired movement, whether or not certain maneuvers are feasible and what forces need to be generated to move or remain in contact with a surface in zero gravity. At this time, we can simulate different movements to see how the robots will move and in which directions. This allows us to see which locomotive pattern is the most efficient. The next step is to add some functions that can simulate the different forces involved.

First, the program initializes the body: position is (0,0) and each limb's extremities are created in the matrix M. It can simulate the four, five, and six limbs configurations. Figure 2.4 shows how all the elements are integrated in a square matrix composed of other square matrices that represent each element's position, on its diagonal.

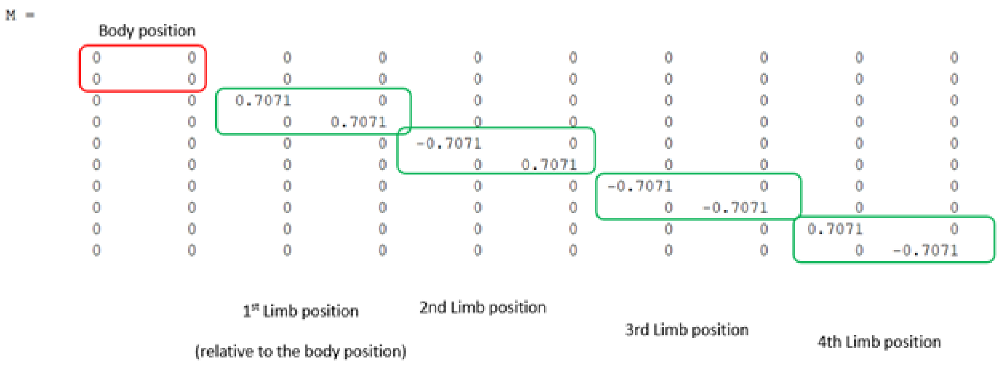


Figure 2.4: An example of the main matrix M that represents a four-limbed soft robot.

Then, we created functions that simulate contraction or extension of a limb in which we can control multiple parameters e.g. length of the limbs, ratio between normal state and bended one, efficiency of the displacement, etc. Finally, we created functions that simulate a full cycle, display the new body center position after one cycle, and represent the locomotive pattern step-by-step. Figure 2.5 shows a representation of the gait pattern for a five-limbed geometry. The contracted limbs are highlighted in red while the others are in blue.

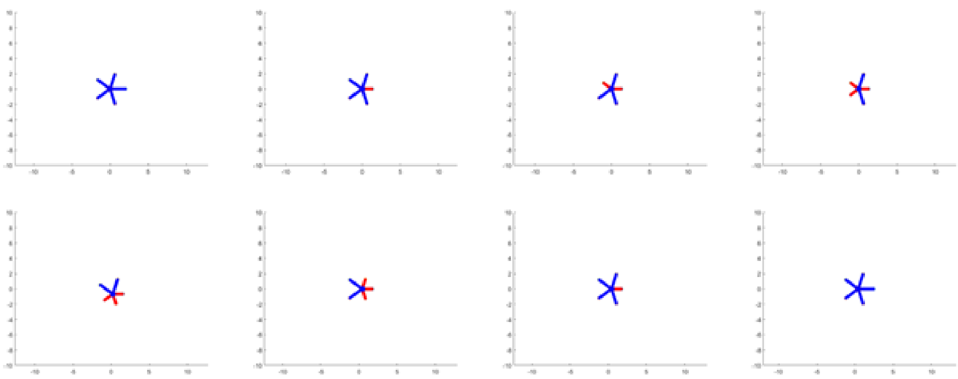

Figure 2.5: Gait pattern of a five limbs model, the robot goes forward.

### 2.2.3 SMA "Skeleton" - PCB Schematic

Shape memory alloys are a group of metallic materials that can "remember" their original shape and return to it. The most common SMA is called NiTinol, equal parts nickel and titanium. Indeed, the latter alloys can return to their initial shape after being deformed depending on specific temperature and stress conditions. This is possible because these alloys can be in two main phases with very different mechanical and electrical properties, depending on its temperature: martensite for low temperatures and austenite for higher temperatures (around 100 °C). In its martensitic phase, the alloy can be easily deformed. It has an asymmetric parallelogram structure allowing 24 orientation variations. The austenitic phase has a body-centered cubic crystalline structure which does not allow orientation variations. Thus, when the deformed SMA wire is heated, its crystalline structure will pass from the martensitic to the austenitic phase and regain its initial shape. This phenomenon is called the martensitic transformation. As a result, it generates a force which is the operating principle of SMA wire actuators.

To actuate STARFISH we designed an SMA "skeleton" very much inspired by work done by researchers at the University of Science and Technology of China, Hefei, Anhui and the University of Wollongong, Wollongong in Australia [5]. In their work, they build an SMA wire actuator using seemingly one SMA wire threaded through two protoboards on each end. It's placed within their CAD modeled limb mold, propped up by various studs to lay flush with the top of the mold, and finally encase it and a PVC plate (to rigidify and provide extra support during locomotion) in PDMS through a two-step curing process. Our "skeleton", however, is designed to have multiple SMA wires soldered onto two PCBs which allow them to be supplied with power. We are adding an electro-adhesion tile on the limb extremity which is in contact with the ground so that our robot can have better grip on all surfaces, including under weightless conditions (zero-G). Figure 2.6 below shows our preliminary design of the SMA "skeleton".

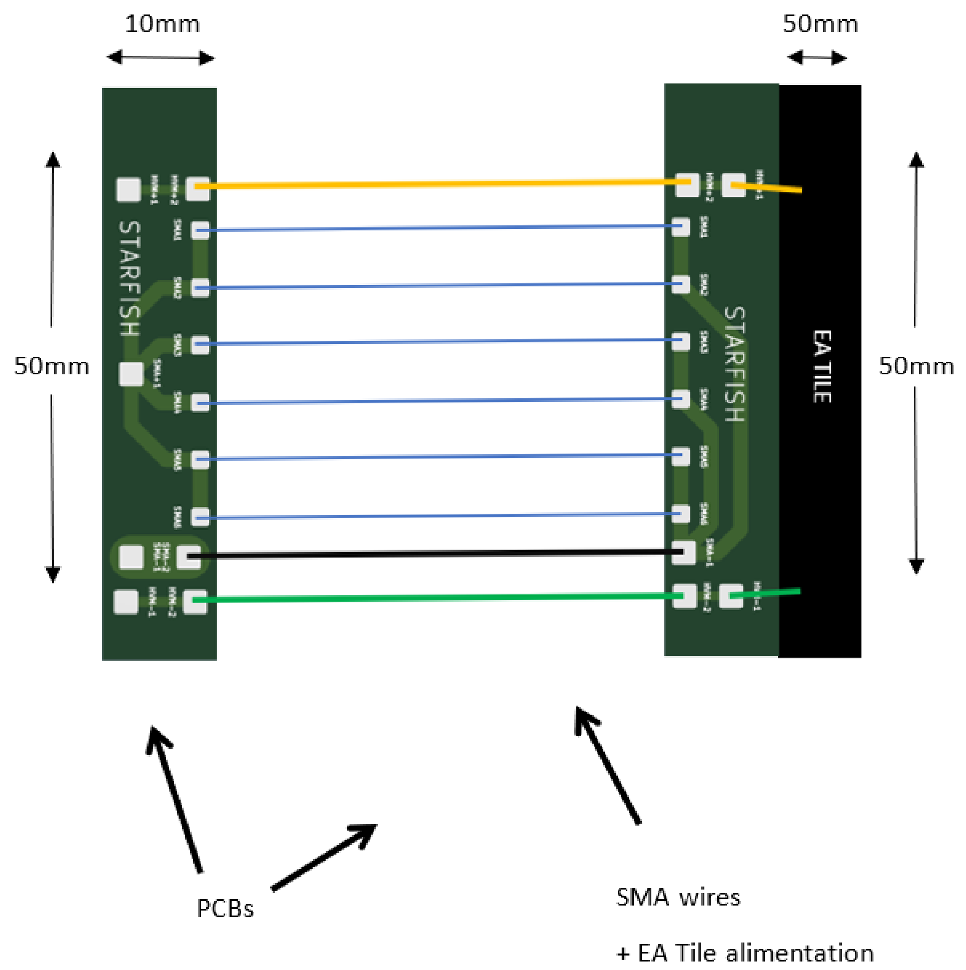


Figure 2.6: Gait pattern of a five limbs model, the robot goes forward.

The two PCBs are linked by the SMA wires soldered to it and two power wires for the electro-adhesive tile and by a power wire that ensures the current returns from the SMA wires. The entire "limb" will be cast in very soft, strong, and stretchy material called Ecoflex™ (or variant from Smooth-On, Inc.) along with the thin PVC plate to form the robot limb. Figure 2.7 depicts a schematic representation of our model.

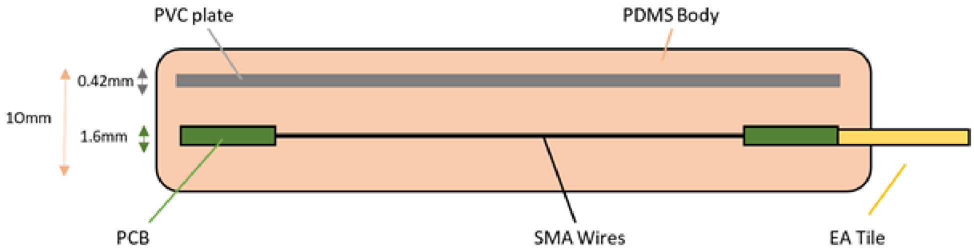


Figure 2.7: SMA "skeleton" composed of two PCBs, EA tile and SMA wires.

### 2.3 Grip Technology - EA Tiles and Gecko

Electro-adhesion(EA) is a unique method to use electrostatic charge to provide a surface contact that resists pull. Shear force can be administered by applying EA patches to an object, which enables mechanical translation or grip if patches are placed on opposing sides. Electrostatic adhesives function on the principle of utilizing a controlled electrostatic field to generate surface polarization to provide a weak attractive force with a wide variety of substrates. Alternatively, Gecko-like adhesives utilize the principle of Van der Waals to create inter molecular attraction forces based on the generation of a high real area of contact. Figure 2.8 shows examples of both the active (electrostatic) and passive (Gecko-like) adhesive technologies that we propose to build upon.

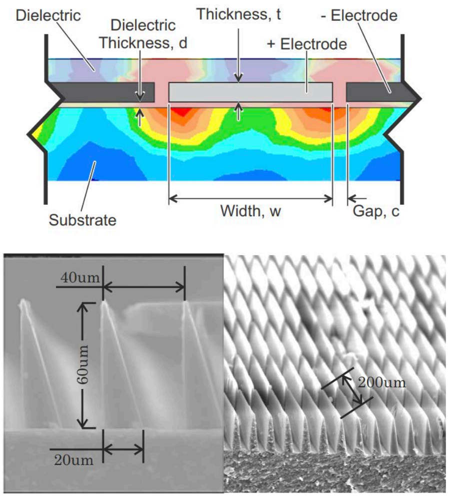


Figure 2.8: Cross-section of a normal electrostatic adhesive and profile view of dry adhesive using "gecko" inspired [6].

EA functions by utilizing a high voltage differential across a set of inter-digital electrodes to generate a strong local electric field. This electric field polarizes the surface material creating a surface charge buildup and thus adhesion occurs [7]. The advantage of electrostatic adhesion is that it generates an adhesive force on a wide variety of surfaces ranging from glass and steel to rougher surfaces such as wood and concrete. This is in contrast to other adhesion methods such as micro-spines, suction, electro-magnetics, and other techniques that can be very surface specific [8] [9] [10]. The disadvantages of electrostatic adhesives are that the adhesion level is relatively weak and is highly dependent on the separation gap between the adhesive and target substrate. EA is shown to be one of the more robust attachment mechanisms since it is both controllable and effective over a variety of surface roughnesses and compositions including conductors, semiconductors, and insulators [11]. Electrostatic adhesives are especially promising for space applications because they can operate in a vacuum, do not utilize chemical bonds, and require no pre-load force on the target surface.

"Gecko", or dry adhesives, are based on behavior traits of geckos [12]. The "adhesive" consists of a micro-structure surface which is used to create a large real area of contact with a substrate and generate adhesion through Van der Waals forces. Two different varieties of dry adhesives generally exist; non-directional and directional dry adhesives. Non-directional dry adhesives typically consist of micro-scale straight vertical stalks with a mushroom shaped tip to provide improved contact area [13]. They typically generate high adhesion on very smooth surfaces, but are not controllable and lack confirmation rough surfaces. Directional gecko-like adhesives, on the other hand, are typically asymmetric structures which deform to provide geometric local compliance with the target surface and generate adhesion when loaded in a preferred direction. Loads sensitivity of the adhesive provides a form ON/OFF controllability and greater micro-scale surface conformation. Directional dry adhesive that USC SERC used under its REACCH effort was developed at JPL and consisted of microscopic triangular wedges about 20µm wide at their base, 60-70µm tall, and about 200µm long (see Figure 2). The adhesive or wedges have directionality in that they use asymmetric micro-structured hairs' (the wedges) bend to create a high area of contact when loaded in the preferred shear direction.

JPL also showed a hybrid combination of Electrostatic adhesion (or EA) and Gecko-like adhesion increased shear force applied to any object and multiple substrates[14]. This is achieved with the EA/G through a synergistic relationship between these two primary adhesive mechanisms. The electrostatic adhesive provides initial clamping to the target surface and allows for macro scale surface conformation due to the generated attraction force and flexibility of the EA film. This high surface contact then allows a significant percentage of the gecko-like adhesive hairs to engage with the target substrate when loaded. As the gecko-like adhesive hairs engage, the provided micro-scale surface shapes conform and reduce the gap distance between the EA and substrate, further increasing its effectiveness. This interaction provides the synergistic effect that enables greater overall adhesion which is often greater than the sum of the individual adhesives. This effect was taken advantage of with REACCH to allow expanded effectiveness on a wide range of target substrate materials.

### 2.4 Soft Material Substrate

The specific prototype development process was focused on proof of concept, not space rated material properties quite yet. Thus, the team looked at using simple and low cost soft materials. Ecoflex™ was chosen as a simple and quick material to create soft bodies. Multiple molds were created to test out the specific curing time, thickness levels, and geometries. Figure 2.9 shows an early example of substrate used in a test arm.

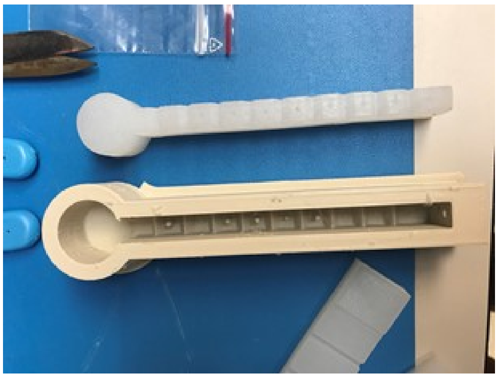

Figure 2.9: Early arm mold and arm made using Ecoflex™ 00-30.

Materials that are soft conform to a specific hardness rating. We investigated the 00-30 Shore Hardness rating in our first instantiation. The Shore Hardness scale was designed to provide a common reference for softness/ hardness of different materials. Shore 00 represents very soft rubbers and gels, and Shore 00-30 will have a similar hardness to a soft-gel shoe-insert.

| *Ecoflex 00-30 data* | |
|---|---|
| Specific gravity | 1.07 g/cc |
| Specific volume | 26.0 cu. in/lb. |
| Shore hardness | 00-30 |
| Tensile strength | 200 psi |
| 100% modulus | 10 psi |
| Elongation at break | 900% |

Figure 2.10: Ecoflex 00-30 data

The team also investigated the use of “soft 3D printed materials” that retain a higher level of compliance after they are extruded than normal ABS plastic. Flexfill 98A was used to test out printing “bodies” that would retain some flexibility connected to the limbs during our prototype development.

### 2.5 Limb and Body Geometries

Several basic single-“limb” designs were established for individual testing during the earliest phase of the project. Phase 2 would consist of connecting all “limbs” to one base and testing the STARFISH in its entirety. Early limb designs were modeled after the fingers of a gecko and consisted of thin rectangular arms with larger circular cylinders on the end of the arm [See Fig. 2.9]. The latter designs were made to encapsulate the SMA wires in the center of the arm and provide enough space at the end for the adhesion tiles to be placed. Current iterations of the limb mold designs consist of one with a constant thickness and another with a decreasing thickness towards the end of the “limb” [Fig. 2.11 below] The molds are designed to be filled with Ecoflex™ or a Smooth-On, Inc. variant.

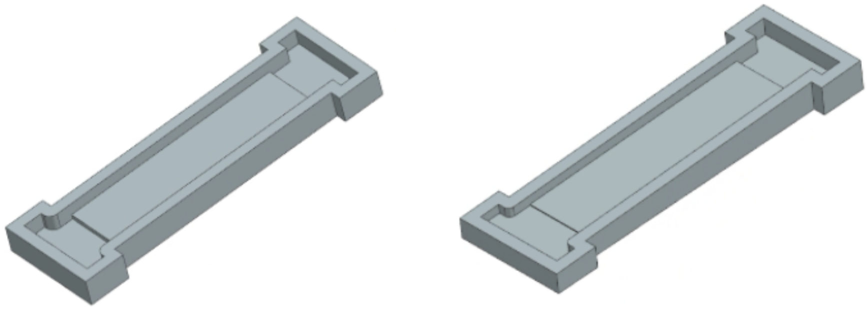

Figure 2.11: Two limb molds : one symmetrical and the other has a 1.5 degrees inclination

During the course of “limb” development, we also began to look at the overall geometry of limbs connected to a central body. Much like a starfish found in nature, our design used a central body to contain the interconnected power, control, and combination sensor unit. Multiple geometries were considered and designed to hold multiple “limbs” in place. A few base geometries are depicted in Fig. 2.12 below. The hexagonal and square body design include lids that are secured with pegs for attaching the limbs to the body. The circular body design, on the other hand, will utilize a twist-on lid.

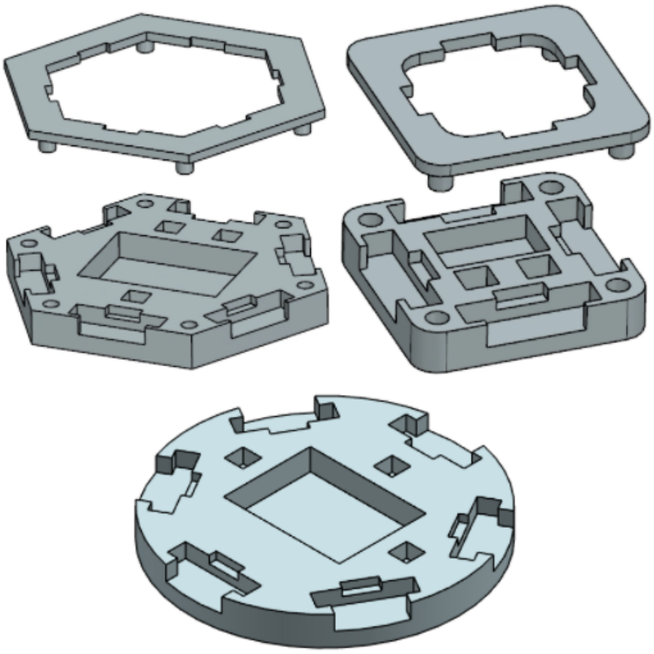

Figure 2.12: Four- and six-edged and circular six-“limbed” base models.

## 2.6 Systems Development

### 2.6.1 State diagram

The basic control methodology will follow the logic of a finite state machine. According to this model, our STARFISH prototype will begin in a static initial state where all the legs are on the ground and it is motionless. Once it moves, the robot will transition from the static state into the correct state given the desired direction. The robot will then be in that state until either given a new state, a different direction, or stopped.

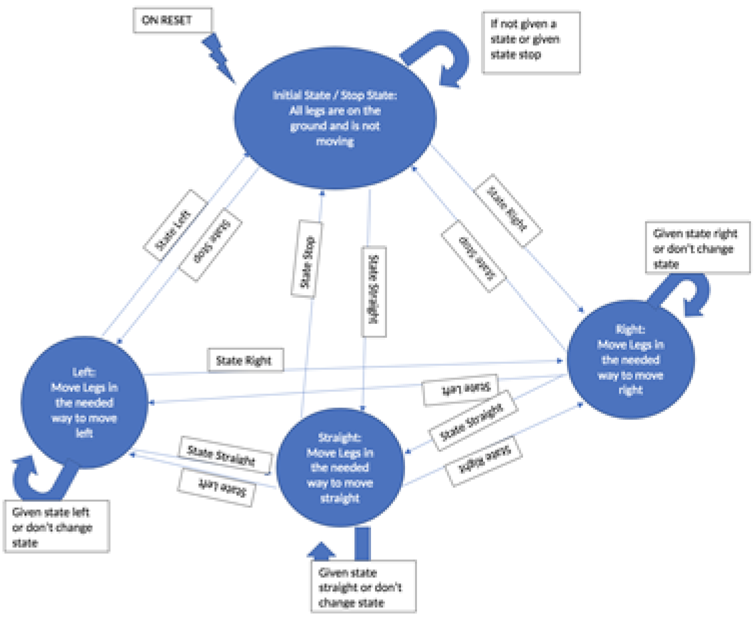


Figure 2.13: State diagram.

### 2.6.2 Electrical schematic

STARFISH will be controlled by an Arduino MEGA board. Since the SMA wires require a high power supply and current that cannot be supplied by the SD card, we will drive power MOSFETs to distribute the current supplied by the 5V batteries to the SMA wires. Likewise, we created a power circuit dedicated to powering the electro-adhesion tiles through the use of Ultra-Miniature High Voltage DC to Dc converters or HVMs, as noted in the figure of the electrical diagram for one "limb" below.

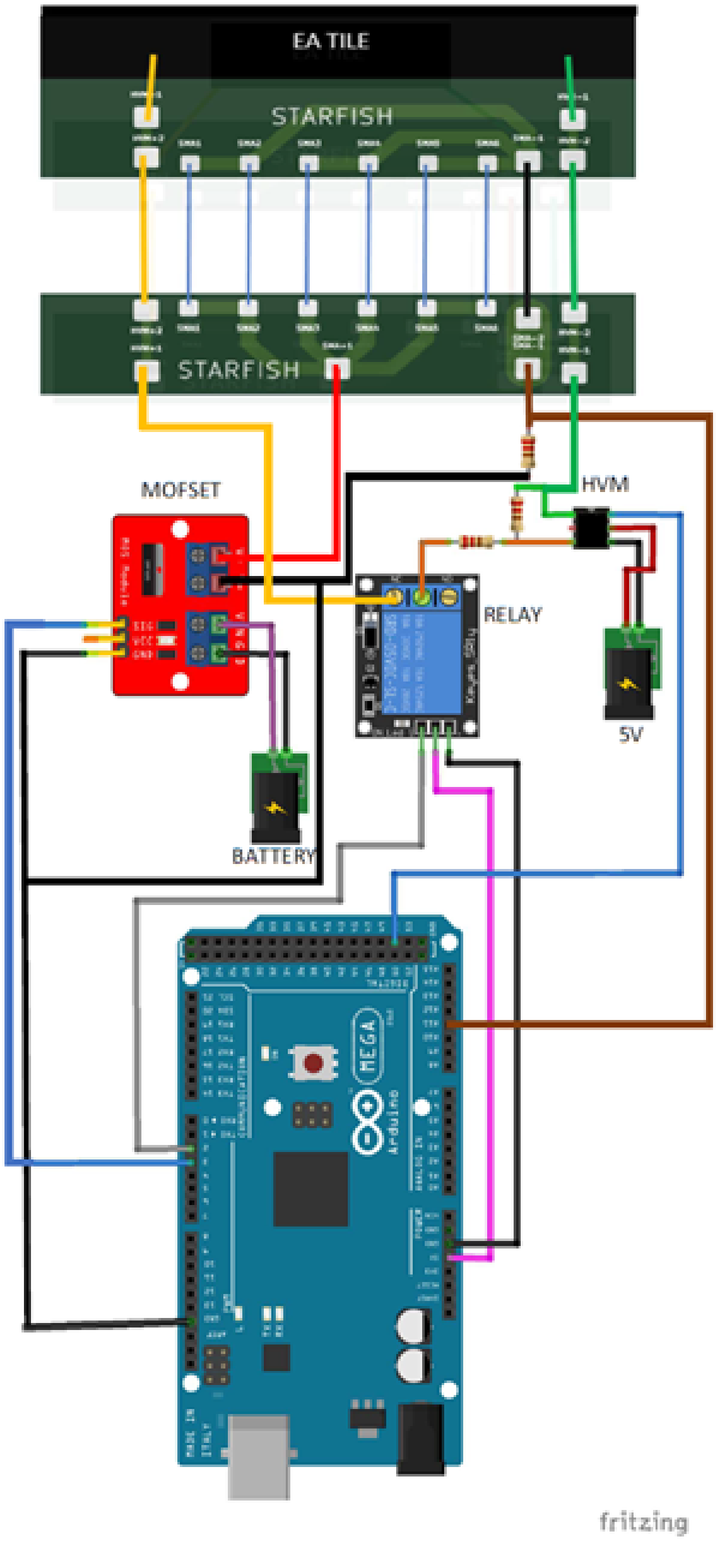


Figure 2.14: Electrical diagram of a limb.

**Analysis and Results**

## 3.1 Actuation

### 3.1.1 Stress and Strain

As we have seen, the martensitic transformation of the SMA wire allows it to pass from a deformed state to its initial state and it is this change of state which creates its movement. To better understand the deformation phenomenon and shape memory principle, we can study the stress/strain curve of a shape memory alloy material, which is shown schematically in Figure 3.1. The properties being different depending on the proportion of the two phases constituting the alloy, an hysteresis appears. It appears that the same stress applied to the wire will cause a much greater deformation if it is in its martensitic phase than if it is in its austenitic phase. Thus, forcing the phase change by heating the actuator under stress will change its deformation and create the movement. Figure 3.2 recaps the different stages of the principle of an SMA actuator.

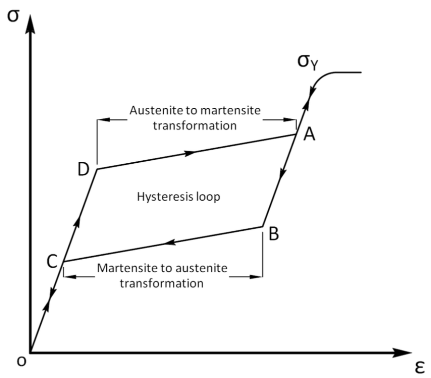


Figure 3.1: Stress and strain curve for SMA.

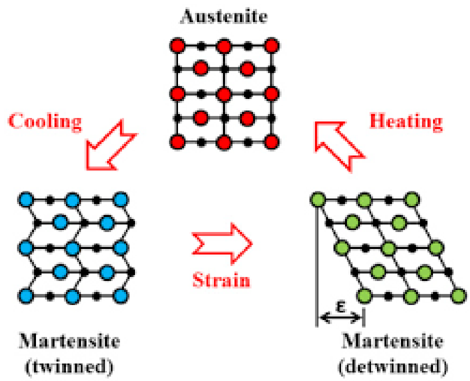


Figure 3.2: Change in crystal structure of SMA.

We are using two different diameters of Flexinol® muscle wire actuators. Their main characteristics are listed in the table depicted in Figure 3.3 below.

| *Diameter* | *150 µm* | *250µm* |
|---|---|---|
| *Activation temperature* | 90°C | 90°C |
| *Linear resistance* | 55 Ω/m | 18.5 Ω /m |
| *Recommended current* | 410 mA | 1050 mA |
| *Recommended pull force* | 321g | 891 g |
| *Recommended deformation* | 3-5 % | 3-5 % |

Figure 3.3: Characteristics of two different Flexinol® wire actuators

These actuators, as noted in the table, have a very good force/weight ratio, much higher than that offered by traditional actuators such as electric motors [15].

### 3.1.2 SMA Analysis - Current and Resistance

The structure transformation that operates when the SMA wire is heated also causes a variation in its electrical properties, so the linear resistance of the wire depends on its temperature. The easiest way to heat the wire is to use the Joule effect by passing an electric current through it. So, in order to prevent overheating and therefore damage the wire, we can control its temperature by monitoring its resistivity. For this purpose, we need a calibration curve establishing the Resistivity/Temperature relationship to control the current that we will send through the wire. The experiment has not yet been carried out with the SMA wires that we have, but the figure 3.4 below shows an example of the relationship described:

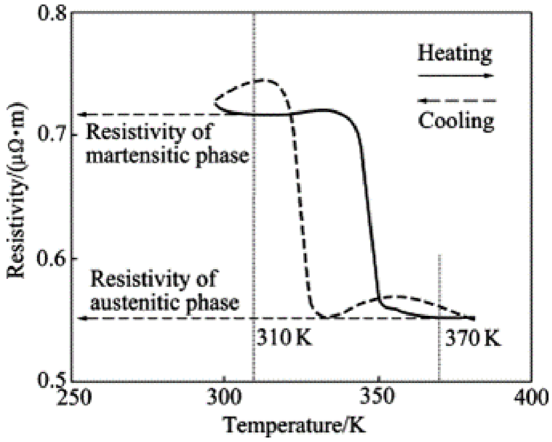


Figure 3.4: Temperature and resistivity curve for SMA.

Once again, we notice the non-linearity of the properties of the SMA wire which forms a hysteresis cycle. This curve will allow us to define two resistance thresholds for which we can consider that the wire is in its martensitic phase: R = Rm or in its Austenitic phase: R = Ra. We immediately have Rm ≥ Ra. Thus, it will be imperative that the resistivity of the actuator does not go below Ra, so as not to overheat it.

We can then establish a first current control strategy according to the resistivity of the wire according to this law:

$$I(R) = Irec * \frac{Rm-R}{Rm-Ra}$$

*Irec* being the heating recommended current, defined by the manufacturer.

The value of the resistivity can be related with the strain ε of the SMA wire and therefore with the position of the “limb” being operated. This is called the "resistance feedback".

**Future Developments**

Future developments in the project will include coming up with a substrate for the skin that can function effectively in extreme space environments. Considerations will be made for variance in temperature, effects of micro-gravity, radiation, MMODs, and other environmental factors. Unlike robots that use actuation methods typical of soft robotics, pneumatics or hydraulics, the STARFISH is actuated by SMA wires, which will require a skin with properties different from a robot actuated by hydraulics in micro-gravity. Commercially available substrates will likely be unable to meet both the need for durability for a space environment and the lightweight flexibility desired for SMA actuation. In finding or designing a new substrate, we will need to optimize the flexibility and heat capacity for the sake of the SMA wires, while maximizing durability against radiation, temperature changes, and other extremities of space. In other words, developing a more robust testing matrix for all individual components as well as the integrated STARFISH itself.

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