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STARFISH: Soft Translatable Actuated Robot for in Space Handling

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Abstract

Humanity's presence in space is expanding, as is our need for larger scale structures to accommodate that presence increases. This presents a set of challenges, one of which is the ability to constantly survey and maintain structures mechanically, electronically, and structurally from assembly through, and past, completion. Project STARFISH developed a plan for a biologically inspired, multi-limbed, shape memory alloy actuated soft inspection robot that combines soft materials with robotics and electro-adhesion and gecko adhesion technology to maneuver on surfaces. While soft robots have been tested and proven in both terrestrial and aquatic environments, space applications for soft robots are lacking. Methods that utilize traditional terrestrial based soft robotic methods fall short in zero gravity, where fluids behave differently and conditions are significantly harsher. STARFISH employs an actuation method that uses shape memory alloy wires combined in parallel, encased in a polymer shell, to produce movement in a zero gravity environment. In this phase of the project, focus was put on validating the shape memory alloy wires as an actuation method, assembling electronics, and configuring different prototype possibilities for testing. STARFISH is meant to prove that independent highly compliant and flexible system that can be deployed onto a space platform that is being assembled/built/serviced in some way, is cheap to make and operate, and can run entirely on solar power, may greatly enhance and accelerate on-orbit validations of new servicing or manufacturing processes.

Keywords: Inspection, Soft Robotics, shape memory alloy, University

1 Introduction

As the advent of on orbit servicing comes of age, the ability to build larger structures in space, assemble, repair, augment existing or new space platforms presents unique opportunities and challenges. One of the challenges is validation and verification of an assembly process, done solely in Space. Activities that connect, sinter, deposit materials, weld or fuse etc. may require evaluation and validation of the process used on the space platform from the various servicing methods. The inspection of the resulting process in zero-g and vacuum of very large non-linear assemblies of various structural/electronic/manipulation elements can be done with free floating stand-off devices, but these require independent rendezvous and proximity (RPO) control to traverse changing structures and avoidance of damaging the object they are inspecting. Whereas terrestrial construction and assembly and servicing actions has vantage points for up close human and sensor validation of joints, assemblies, connections, welds, and deposits along with the quality of materials used in the process, this aspect of quality assurance that comes from "in person" inspection may not be possible in space servicing applications. Thus, having a ubiquitous, independent highly compliant and flexible system that can be deployed onto a space platform that is being assembled/built/serviced in some way, is cheap to make and operate, and can run entirely on solar power, may greatly enhance and accelerate on-orbit validations of new servicing or manufacturing processes.

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 or space platform for the purpose of coupled or close in 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. In development the team focused on some key elements to start with, designing body and limb geometries for ideal movement and "grip". Additionally, the team looked at locomotion methodology, electronic requirements, and shape memory alloy actuation behavior.

This paper will address development and casting of various limb configurations for testing, optimizing the software to cut back on hardware requirements (see: duty cycle), and assemble a semi-functional prototype for analysis. Our goals remain assembling a fully functional prototype capable of not only movement, with the ability to maintain contact with a surface while moving in a zero gravity environment.

2 Background

How is autonomous on platform inspection of space system assembly done today? It's not! The advent of "building" platforms in space through autonomous robotic systems is still very new. All space systems typically go through validation on the ground with environmental test prior to launch. But for new assemblies in space built without direct human contact there are limited methods to provide that validation post build or assembly, externally. The inspection of resulting mechanical or electrical assemblies in zero-g/vacuum of non-linear assemblies with various structural/electronic/manipulation elements may be done by free floating stand-off devices or proximity robotic end affectors, but these solutions are costly, complex, and limited in scope. A solution here is to place an inspection or validation device directly on the surface of the newly assembled platform. The system would need to be flexible to multiple geometries, scale-able to different sizes, use very low power, and be extremely light weight and very low volume to pack onboard spacecraft. STARFISH is meant to provide that potential solution. Our team at the SERC considered a number of potential methods to do verification and validation or inspection of non-linear constantly evolving assemblies in space. STARFISH falls at the intersection of simplicity, low mass, and ease of placement 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. A vital piece of technology carried over from REACCH is Electroadhesive/Gecko adhesion technology, which utilizes low amounts of power to generate a high amount of grip. Historically, in-space capture is executed through pre-defined and mechanically fixed interfaces - REACCH offers the ability to service a variety of satellites and space structures without pre-determined grip interfaces. [**1**] 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 expands on the REACCH concept incorporating tried and true concepts of soft robotics with Electro/Gecko-adhesion technology to create a "walking" inspection robot that is fully compliant, and that survives in space. The EA technology relies on small scale electrical interactions [**2**] [**3**] while the gecko technology mimics the van der Waals adhesion from gecko setae via micro grooves and fibers [**4**] [**5**]. STARFISH is also bio-inspired as it looks and operates similarly to its namesake, 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. 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".

In robotics research 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 robotic concepts and STARFISH. Figure 1 shows a graphical example of a notional trade space metric against the various area of utility of some existing robotic devices for space. Some other key challenges include maintaining grip and moving while maintaining that grip with the surface in zero gravity.

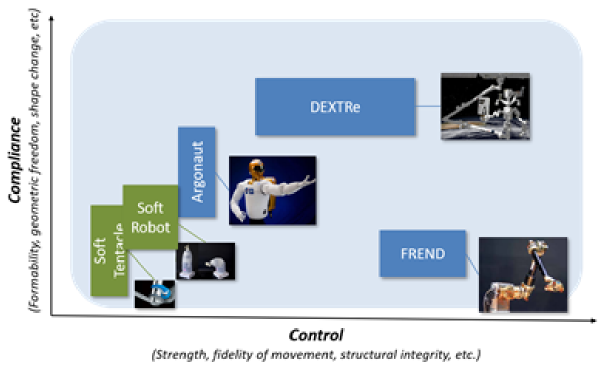

Fig. 1: Compliance versus control

Previous work has discussed the underlying factors that make STARFISH possible. This paper extends those factors, and looks at developing actual functioning limbs, bodies, and electronic assemblies for the STARFISH.

3 Design and Models

3.1 Locomotion Methodology

Initial research was performed to better understand what sort of locomotion or gait would be employed, and what would the potential pitfalls or constraints might be in place as we developed the prototype. A model is shown below (Figure 2), showing the activating of certain limb combinations to achieve movement in a specific direction. More detailed results are listed in our previous paper as well.

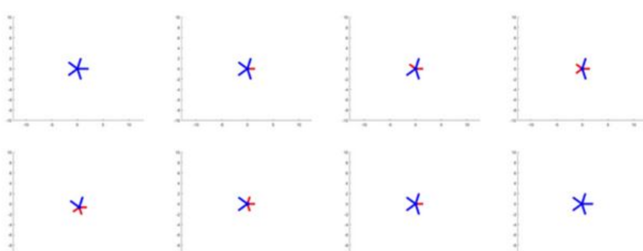

Fig. 2: Gait pattern, active limbs in red

Our decision to use shape memory alloy wire based actuation came from the realization that typical soft robotics methods, which would be able to achieve the actions needed to generate movement, would be hindered by the shortcomings of fluid behavior in zero gravity environments. [**6**] [**7**]

3.2 SMA Skeleton

Shape memory alloy wires are a thin, hairlike wire that have an interesting behavior - when heated past a certain temperature, they change shape, returning to a previous state configuration depending on the manufacturing process. The most common SMA is called NiTinol, equal parts nickel and titanium. Shape shifting is dependent not only on temperature, but also stress experienced by the wires. 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. Martensitic phases can be easily deformed due to asymmetric structure, while austenitic phases have a crystalline structure which does not allow orientation variations. The transition from martensitic to austenitic is known as the martensitic transformation, and it results in a return to initial shape, generating a force which drives SMA wire actuation methods.

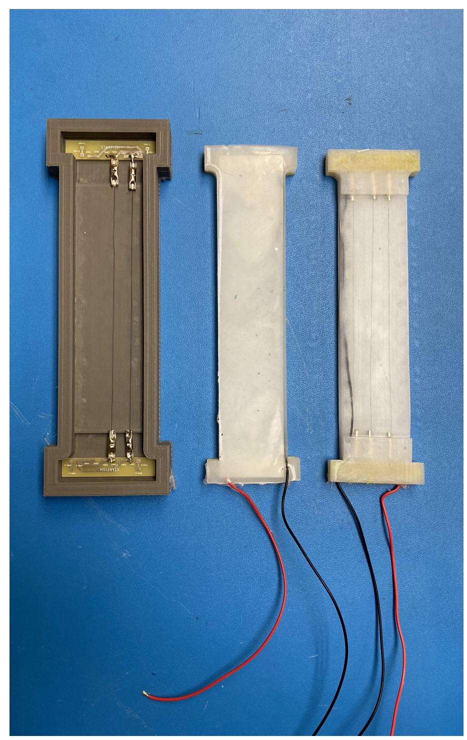

Fig. 3: STARFISH skeleton and fully cast limb

To actuate STARFISH we designed an SMA “skeleton” inspired by work done by researchers at the University of Science and Technology of China [**8**]. 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 mold, propped up by various studs to lay flush with the top of the mold, and finally encased with a PVC plate (to rigidify and provide extra support during locomotion) in PDMS through a two-step curing process (Figure 3). 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 generate a strong grip on non-terrestrial surfaces, including under weightless conditions (zero-G).

3.3 Limbs

3.3.1 Substrate

The characteristics of the substrate used in the casting of a STARFISH limb are listed below.

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%

Fig. 4: COTS Substrate Data

3.3.2 Assembly and casting

Our limbs are made up of a skeleton composed of two printed circuit boards connected by Shape Memory Alloy wires and a commercial, off the shelf polymer. The polymer, also used in Hollywood prosthetics, provides for terrestrial prototyping and testing, suitable flexibility and coverage to mimic the desired end result of a space certified polymer. The SMA wires are tied to small loops at the end of thicker, traditional wires and crimped in place – the traditional wires are then soldered to the PCBs, such that the SMA wires are preserved during the soldering process, along with power wires which protrude outside the polymer skin of the arm. The assembled skeletons are then placed in an arm mold such that the SMA wires are taut – this is an important step, as loose SMA wires will not provide the necessary level of bend for motion. A first layer of liquid, uncured polymer is poured into the mold, followed by a thin, flexible, 3D-printed rectangular plate that provides support to the limb and directs the bending movement. A final layer of polymer is poured, and the entire setup is allowed to cure overnight. The final product is a flexible and soft system for actuation.

To test for ideal limb function we cast several different types of limbs with different thicknesses of shape memory alloy wire skeletons, different skin materials, and different arm bar thicknesses. Thinner arm bars provide greater bend but less stability. Thinner SMA wires improve the total bend amount to a certain degree, after which thinner SMA wires don't provide a significant advantage. The skin materials we tested did not significantly impact the final bend or functionality of the arms.

3.4 Body

Several bodies have been designed by the team for the robot, models that can fit 4 to 6 limbs (Figure 5). While a STARFISH with 6+ limbs will most likely be the ideal final product in terms of being able to both move and maintain a grip force on a surface, short term prototyping and proof of concept could be demonstrated more simply with the 4 side bot. During prototype tests we found the body to be too heavy for 1g movement, however 0g movement would not be hindered.

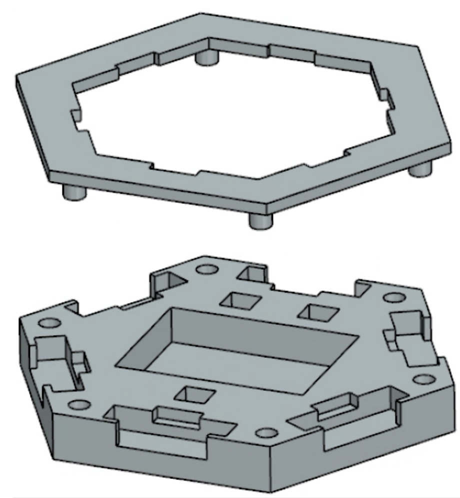

Fig. 5: Hexagonal STARFISH body

3.5 Prototyping

Our team assembled a four limb STARFISH for prototyping purposes. The arms proved to not be strong enough to move the robot in 1g, however the limbs did demonstrate a significant range of motion, with bends at the midpoint reaching 90 degrees and beyond. In zero gravity the main force requirement would be the force directed in towards the surface on which the robot is crawling to not lose contact while in operation. The prototyping that took place was also done without our electroadhesion/gecko tiles, which greatly improve the generated gripping forces, allowing the robot to move while maintaining grip on off-nominal surfaces (walls, zero gravity environment). [**1**] [**2**]

4 Analysis and Results

4.1 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. 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. Additionally, the SMA wires have large force/weight ratios, ideal for keeping mass low in a space qualified bot. [**9**]

We have used three different diameters of Flexinol® muscle wire actuators: 100, 150, and 250 microns. The 100 micron wire proved ineffective, any knots placed along it tended to slide apart. The 150 and 250 micron wires both still have good force/weight ratios, significantly greater than force/weight ratios offered by traditional actuators like electric motors.

4.2 Current and resistance

In previous work we established that the structural transformation that takes place when an SMA wire is heated also impacts its electrical properties. This would allow us to control the temperature of the wire by monitoring resistance. However, due to some technological hang ups, we had to work around being unable to measure the resistance constantly.

We analyzed the behavior of the wires in relation to the duty cycle and calculated the proper cycles along which to activate the wires, such that we would not have to worry about overheating or damaging the wires.

In Figure 6, we show the relationship between current and duty cycle for our two different thicknesses of SMA wire.

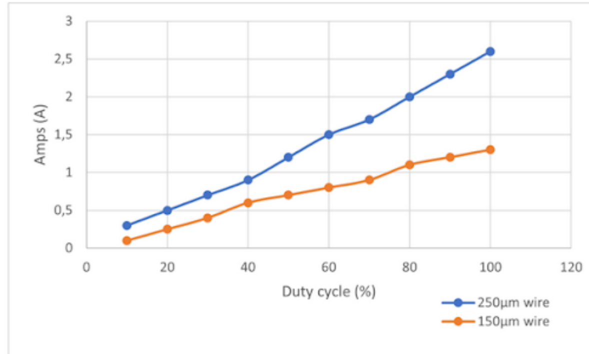

Fig. 6: Relationship between duty cycle and current.

4.3 Limb data

The figure below (Figure 7) shows the vertical displacement data for a single 1kg mass hung from. Change in wire length during contraction is related to the physical properties of the wire. Thinner wires have produced greater displacements as a result of the amount of surface area of the different wires.

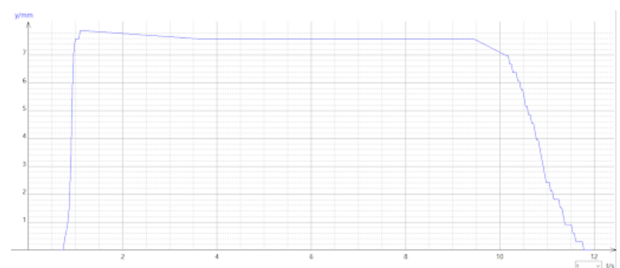

Fig. 7: Vertical displacement of a 1kg weight by shape memory alloy wire.

The ideal limb configuration for maximum bend with adequate stability and arm strength is a 0.4mm to 0.5mm arm bar with 150 micron shape memory alloy wires and a skin made with a soft, flexible rubber. This configuration allowed for a 90 degree and greater bend of a limb, compared to a near 40 degree bend with the thicker arm bar but same shape memory alloy wire, and significantly greater than the 10 to 15 degree bend with the thicker arm bar and the thicker SMA wires. None of these configurations provide the necessary strength alone to move the STARFISH significantly in a terrestrial, 1g setting.

4.4 Software and Electronics

For our purposes, we require the ability to perform multiple processes simultaneously, ie. operating different combinations of limbs to achieve different results. The micro-controller used in early phases of the design and testing process cannot support parallel processing. This wasn't an issue while we were experimenting with single limbs, SMA wire behavior, and the like, but as we increased the number of limbs in testing the problem became apparent.

One thought we had was that we could cycle through the limbs required for a set of movements or actions in rapid fire succession, such that the wires would remain contracted and the limbs bent, maintaining a force on the surface of whatever body the STARFISH is on.

The software "activates" certain limbs by sending a signal through the micro-controller to allow a current generated from a battery to pass through our SMA wires, the actuators. As the current passes through the SMA wires, the temperature of the wire increases, and as it passes a critical point it causes the wire to contract. This happens on a very small timescale. See Figure 8 for a detailed schematic of the electronics.

A goal of the software is to be able to activate multiple limbs simultaneously to create movement and to generate a surface-pointing force to maintain contact with bodies in zero-g environments. This will require adjusting our electronics to account for the need for parallel processing, either introducing a processor capable of multiple simultaneous processes or multiple individual microprocessors.

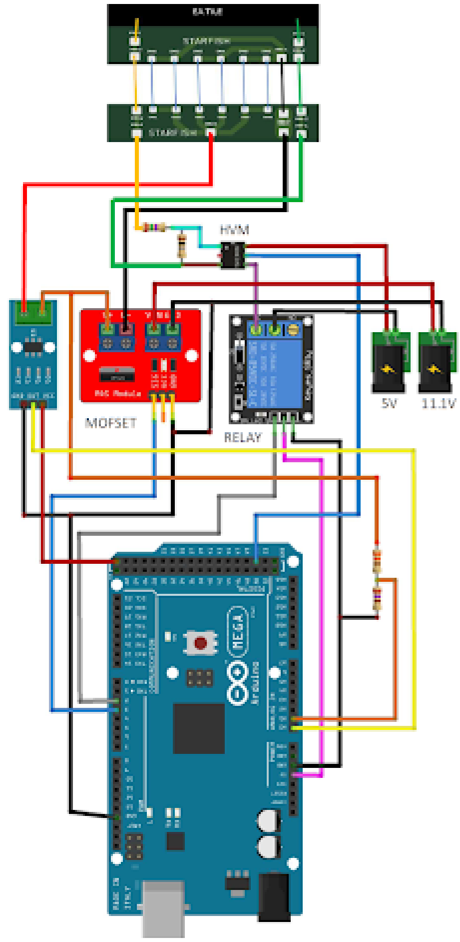

Fig. 8: Electronics arrangement, like a bouquet of beautiful cable management.

5 Future Developments

Our next steps for prototyping are to assemble a STARFISH for the Raspberry Pi system, such that we can demonstrate multiple simultaneous limb actuation. This will require simple reworking of our body designs and writing a new piece of software for the Raspberry Pi OS. Further down the line, we are interested in developing a system in which each limb has its own processor and the entire system is governed by code based on which limbs are active/attached.

Additionally, we will be incorporating the Electroadhesion/Gecko technology into our limbs during mobility and grip testing.

There are also new advancements to be made to the body and limb design that will improve the range of motion. One of these is to add more support around the limb-body joint so that the arm is not too flexible in the wrong direction. As testing progresses, more and more possible improvements become apparent.

6 Acknowledgements

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