Concept Generation

EML 4551C – Senior Design – Fall 2012 Deliverable

Shape Memory Alloy/Polymer Active Surface Shaping for Reflectors

Team # 9

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Introduction

The current generation of satellites are becoming more advanced, but are becoming limited in their ability to compact and store in confined spaces. Newer technologies for reflector configurations for satellites such as mesh reflectors, are used to reduce the overall structure and mass, which decreases the mass by 50% when compared to conventional solid reflectors. With these type of systems sent far out from the reach of technicians, high performance factor with no maintenance is necessary for maximum efficiency.

Using shape memory alloys (SMA), a proof of concept will be tested upon to determine whether SMAs can be applied to satellite reflectors effectively. The SMAs are used to make final adjustments to change the shape of a reflector surface, which modify the optical properties. The idea consists of applying a current through the shape memory element to modify it's crystalline structure and thus change it's shape.

The main objective of this project is to design and build a prototype of a base structure, such as a petal from a deployable satellite dish that will support the SMA material. The frame will then change it's geometry based off an adjustable current, which will make the SMA contract and expand. The design will be used in further research to ultimately apply SMAs to commercial satellites and other applications. This requires the system to be highly versatile with a user-friendly interface that can be easily adaptable, with software such as Labview. Using a computer connected to a breadboard, the SMAs can be actuated via various points along the surface membrane. With no physical parameters specified, the base dimensions of this model should be able to fit on top of a tabletop.

Materials

Shape memory alloys and shape memory polymers were investigated for this project, however there was a need for a two-way shape memory element, meaning the SMA could actuate and then return to its original shape. Shape memory polymers are only one-way, hence once they are actuated, they cannot return to their previous shape readily. Therefore, shape memory alloys were the clear choice for this application.

Shape memory alloys respond to mechanical, thermal, electromagnetic and ultrasonic inputs in a displacive transformation fashion that switches between martsenite and austenite phases. Many uses for SMAs have been explored already in a variety of research areas. SMAs have applications from medical uses for mending bones and reinforcement for arteries and veins, to fire security and protection systems. Most SMAs have been actuated using ambient thermal changes. There has been some research done actuating the SMAs via other methods and this project will actuate the SMAs by passing a current through a SMA wire which will in turn thermally excite the crystalline structure of the SMA.

Investigating SMAs more, it was found that there are several options, such as copper-aluminum-nickel, copper-zinc-aluminum, and iron-manganese-silicon. While all of these alloys exhibit shape memory effects, nickel-titanium has superior structural and memory capabilities hence this would be the logical choice for this project. Nickel-titanium or Nitinol wire is also more readily available and also has a lower cost. NiTi alloys also have much higher strength, larger recoverable strain, better corrosion resistance and most importantly higher reliability than CuZnAl, they are the standard choice for use in space and several other applications.

	NiTi	CuZnAl
Recovery Strain Recovery Stress Number of Cycles	max 8% max 400 MPa 10^5 (ε = 0.02) 10^7 (ε = 0.005)	max 4% max 200 MPa 10^2 (ε = 0.02) 10^5 (ε = 0.005)
Corrosion Resistance	good	problematic, especially stress corrosion cracking

Table 1 Comparison between 2 most common SMAs

Control System

In order for the system to perform properly, a system for measuring the amount of voltage applied to the nitinol wires must be implemented. Various sensors have been considered for use such as strain gauges and fiber optic sensors. Most sensors do not communicate directly with computers, so a breadboard will be employed to condition the signal. Data acquisition software will then be utilized to interpret the signals received from the sensors.

Strain gauges or flex sensors can be used to measure resistance changes in the device as the shape memory alloy causes the surface under consideration to deflect. These sensors will be able to provide an output voltage corresponding to the degree of curvature of the surface they are attached to. The accuracy of the readings will depend on the quality of the sensor. Strain gauges are light weight sensors that are affected by changes in temperature which is undesirable as the device will experience an increase in temperature as the nitinol wires are activated. These sensors are relatively cheap.

Fiber optic sensors can also be used as a type of strain sensor. Some of the advantages these sensors have are that they do not require contact with the surface they are measuring and also they are not affected by temperature making them suitable for this application. Although fiber optic sensors may be preferred for this application their cost may be a deciding factor in their use.

The signals from these sensors must first be conditioned in order to be received by a data acquisition device. Strain gauges are integrated into Wheatstone bridges in order to amplify their small output signals into readable voltage outputs. Conditioning the signal of a flex sensor requires a circuit containing an op-amp to boost the signal received to useful levels. In regards to fiber optic sensors, additional equipment must be purchased in order to read the output voltages from the sensors.

Once the signal has been conditioned, data acquisition software will collect all of the data from each sensor. Programs under consideration for use are DSpace and LabVIEW.

Power Consumption

To find the power consumption required to contract a wire of a certain diameter, electrical properties such as current and resistance can be found in the Nitinol Alloy Wire Performance Characteristics table in the appendix.

$$V = I * R * L \ (1)$$

When the correct amount of voltage is applied, maximum pull force can also be calculated using values from the chart.

$$F = ma \ (2)$$

Concept Generation

Considerations of many different arrangements of SMA wires to actuate the surface into a desired shape were made. Configurations where SMA wire ran radially about a representative petal and horizontal to the surface were considered as well as those where SMA elements were positioned normal to the surface. Various designs were looked at, some utilizing springs in unison with SMA wire and some with very simple parts, utilizing only minimal SMA wire. In any case, Nitinol wire is the commonality in all designs and will be the basis of design for this project.

Concept #1 - Radial SMA

Concept 1 is a representative petal from what would be a complete parabolic dish. Each petal consists of a hub and an outer rim between which a wedge of heat resistant silicone is fixed. Each of the nitinol wires runs through the hub, up through the silicone, and into the outer rim. Set screws hold each wire firmly in place at the outer rim. The outer rim is composed of a thin, lightweight aluminum.

As current is fed in through the hub from the power supply, the nitinol wires will begin to heat up to about seventy degrees Celsius, the activation temperature. This will cause the wires to actuate to their "remembered" shape. The wires will bend the silicone along with them.

Grounding the wires in order to achieve current flow may prove to be a problem. The wires may have to come out of the opposite side of the outer rim in order to be grounded. The process for this design is rather complicated. More nitinol wire has to be used which in turn causes more power to be consumed by the device overall. Due to the fact that this design consists of mainly silicone rubber and the nitinol wire, it proves to be very light weight.

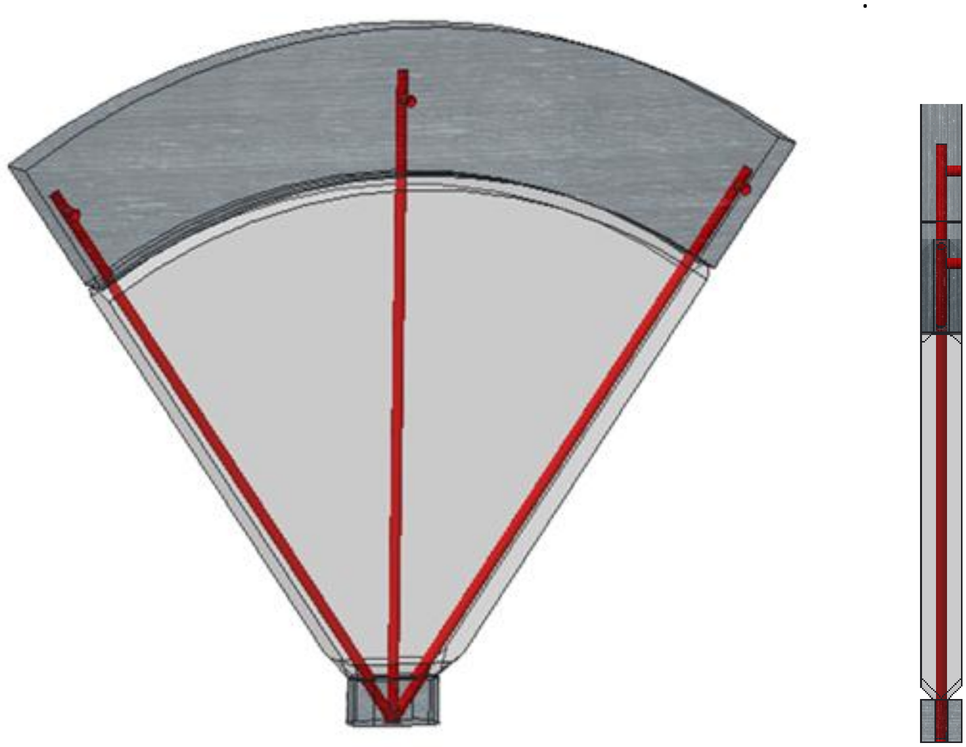

Figure 1 Front and side views of radial SMA design

Concept #2 - Implementing Springs

This concept utilizes springs in tension and compression in order to mechanically deform an elastic membrane. The surface membrane will be made out of an easily pliable material such as shim stock or rubber in the shape of a representative petal found on a deployable satellite dish. Springs are mounted underneath the membrane, on the base of the frame in an ascending fashion that positions the membrane into a parabolic shape. The mounted springs may be elevated to cut costs when compared to longer springs. In between each spring, there will be a SMA wire attached to the membrane that will contract when there is a current applied. As the wires contract, there is a change in the geometry of the surface membrane. When there is not current supplied to each individual wire, the springs will expand and shape the membrane back to the original parabolic configuration.

The use of this design may reduce costs due to less SMA wire required to actuate the geometry change of the surface membrane. However, with different lengths of wire attached to the membrane, the electrical setup for this design may be more complex and require more power consumption.

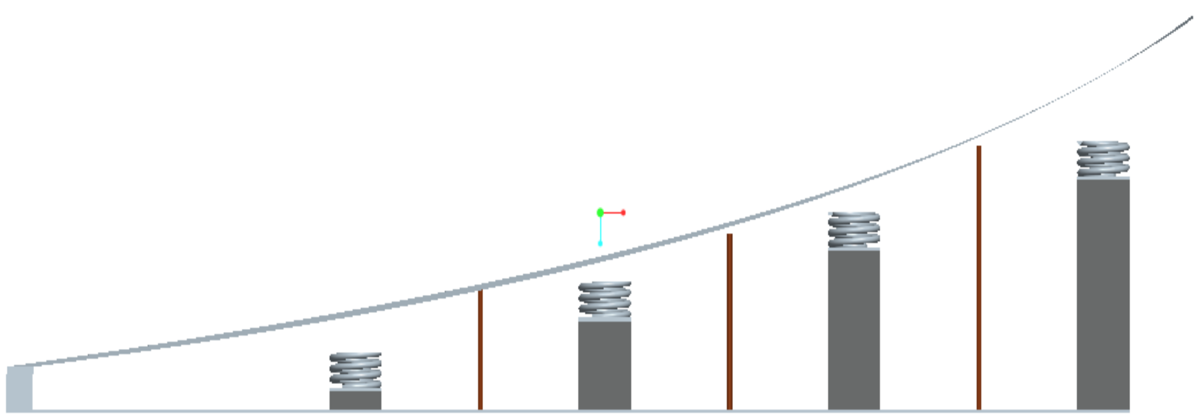

Figure 2 Side view of spring design

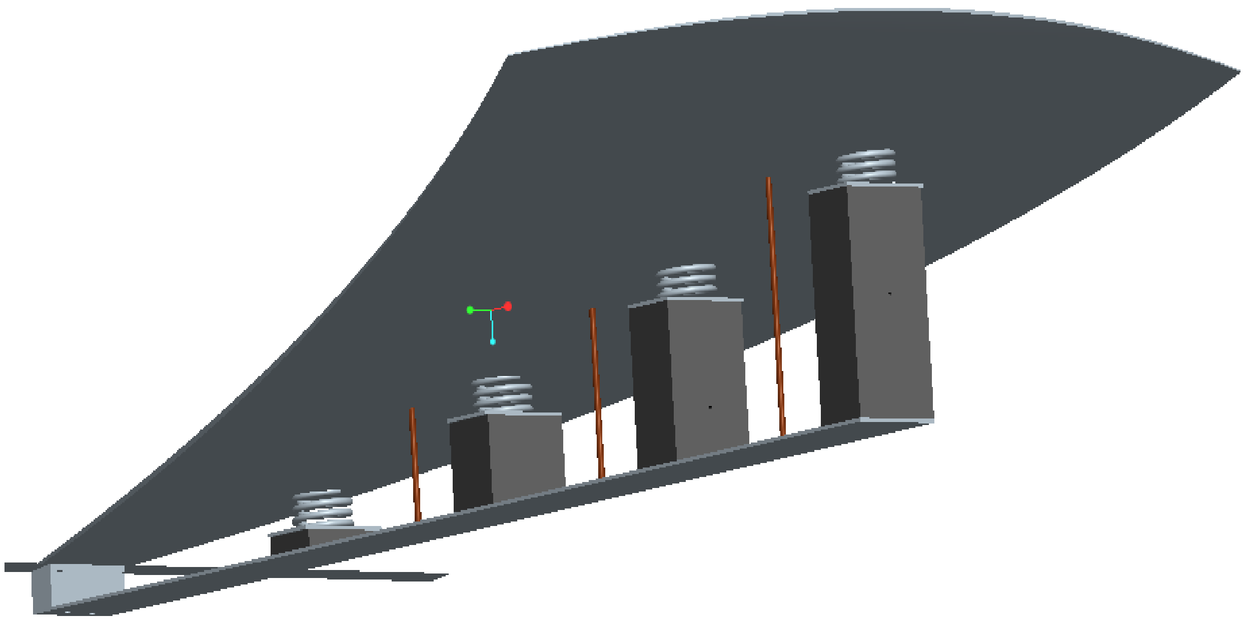

Figure 3 Angled, underneath view of spring design

Concept #3 - The Uni-Cube

This concept is by far the simplest design to date for this project, utilizes a rigid frame and a square piece of shim stock as the membrane or representative surface. Using this shim-stock material will ensure that the heat from the SMA actuation does not melt the surface which in turn improves durability and reliability. This shim stock material will be held on all four sides rigidly utilize a clamping action and machine screw fasteners. In order to fasten the SMA wire to the membrane surface, a crimp on ring terminal will be used and a hole will be drilled through the shim-stock surface and the wire will pass through and a pin will be placed through the hole in the ring terminal. The wire will then be attached in a similar fashion to the rigid frame at the base. When actuated the wire will contract and pull the surface out of plane in a normal direction and cause the shim stock to take on a parabolic shape. This design not only cuts down on materials and cost but also power consumption, since it utilizes only one short piece of SMA wire that needs to have current passed through it.

To find the force to make the surface membrane deflect from a concentrated load at the center, equation 2 is used. This is the deflection equation for a square flat plate with all edges supported above and below, which can be modified to calculated force.

$$D = \frac{0.1266FL^2}{Et^3} \quad (3)$$

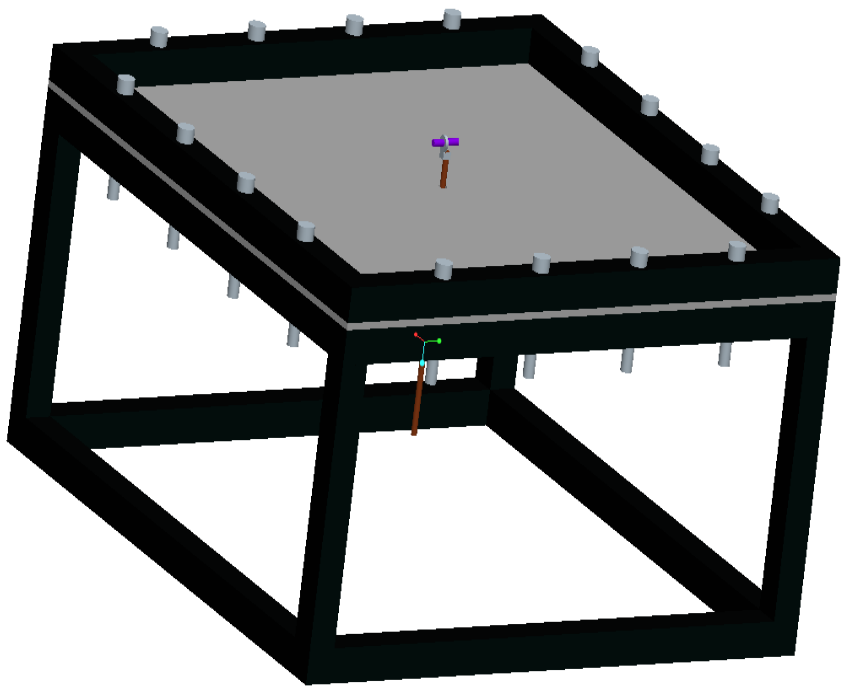

Figure 4 Top view of Uni-cube design

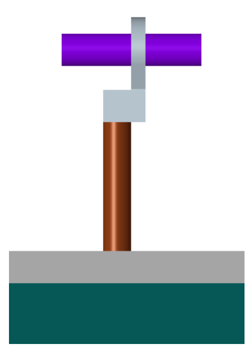

Figure 5 Zoomed in side view of terminal crimp ring

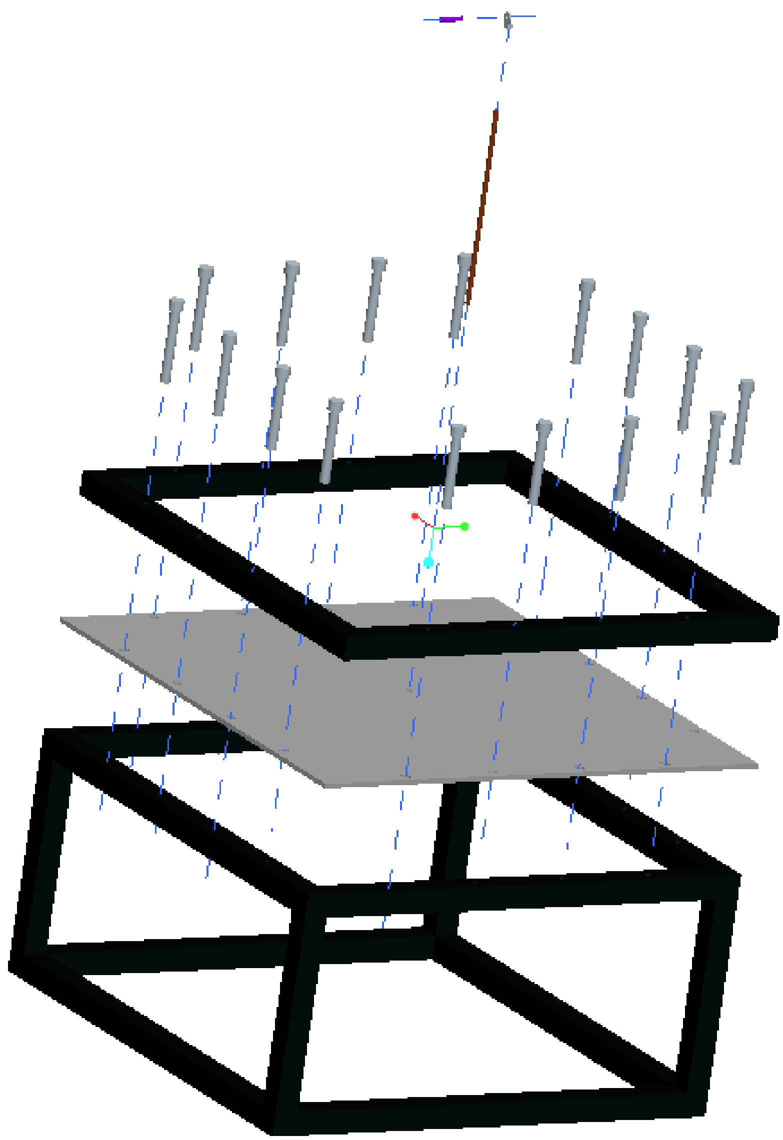

Figure 6 Exploded view of Uni-cube design

Selection Criterion

All of the following designs contribute to some type of surface geometry change; however some fit the customer's parameters better than others. Taking into account current knowledge and understanding of the SMA elements and customer needs each concept was weighted according to reasonable relatively importance.

Anytime a specified budget is given for a project, cost should always be a deciding factor, therefore this was included as a criterion for selection. Since this was not a superior driving parameter, this was not given a big weight at 0.05.

The customer expressed concerns for having a reliable system, therefore this was also a weighing factor. This was an important criteria therefore it was weighted heavier at 0.3.

Durability should also be a standard selection parameter in engineering design, for this project, it was deemed to be moderately important since this is merely a proving ground for SMA control for active shaping and hence a value of 0.1.

The customer also expressed concern about maintaining a smooth surface throughout actuation and shaping. Since the customer explicitly asked for this mandate, a value of 0.3 was given to this parameter.

Often times in order to get a reliable and working design with fewer iterations, it is necessary keep things simplistic. This minimizes chances for intricate problems and extreme re-designs. with this in mind this selection criteria was given a weighted value of 0.2.

Power consumption was also somewhat a driving parameter. Although the customer had no power restrictions on actuation power, it was still something to keep in mind since this control system could potentially be implemented in the field at some point in the future. Power consumption was therefore given a weighted value of 0.05.

After weighing in feasible values for the six selection criterion for the three concepts, it was clear that concept three (Cube) was the best choice to pursue. The near future holds as few more research and design issues to finalize such as power requirements and control system perfection.

Concept Selection (Decision Matrix)

		Petal		**Springs**		**Cube**	
Specification	**Weight**	***Rating***	***Weighted Score***	***Rating***	***Weighted Score***	***Rating***	***Weighted Score***
Cost	0.05	3	0.15	2	0.1	5	0.25
Reliability	0.3	1	0.3	3	0.9	4	1.2
Durability	0.1	2	0.2	3	0.3	4	0.4
Ability to Maintain Smooth Surface Profile	0.3	2	0.6	3	0.9	3	0.9
Simplicity	0.2	3	0.6	3	0.6	5	1
Power Consumption	0.05	3	0.15	3	0.15	3	0.15
Total Score:	1	2		2.95		3.9	

Ratings: 1 (worst) to 5 (best)

Table 2 Decision Matrix

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Appendix

NITINOL ALLOY WIRE PERFORMANCE CHARACTERISTICS

WIRE SIZE (INCHES)	RESISTANCE (OHMS/INCH)	MAXIMUM PULL FORCE (GRAMS)	APPLIED CURRENT AT ROOM TEMP (MA)	CONTRACTION TIME (SEC)	OFF TIME 70°C WIRE (SEC)	OFF TIME 90° WIRE (SEC)
0.001	45	7	20	1	0.1	0.06
0.0015	21	17	30	1	0.25	0.09
0.002	12	35	50	1	0.3	0.1
0.003	5	80	100	1	0.5	0.2
0.004	3	150	180	1	0.8	0.4
0.005	1.8	230	250	1	1.6	0.9
0.006	1.3	330	400	1	2	1.2
0.008	0.8	590	610	1	3.5	2.2
0.01	0.5	930	1000	1	5.5	3.5
0.012	0.033	1250	1750	1	8	6
0.015	0.2	2000	2750	1	13	10
0.02	0.16	3562	4000	1	17	14

Table 3 Nitinol Alloy Wire Performance Characteristics

Sample Calculations for Concept #3 - Uni-Cube

Voltage required to contract length L (current and resistance are found on table 3

$V := R \cdot I \cdot L$ Equation 1

From table 3 above for 0.005" diameter wire

$R := 1.9 \frac{ohm}{in}$ Resistence per unit span

$I := 320mA$ Current

$L := 5in$ Wire contracts 5"

$V := R \cdot I \cdot L = 3.04\,V$ Voltage required to contract 5" of 0.005" diameter wire

$F := ma$ Equation 2

$F := 0.223kg \cdot g = 2.187\,N$ Pull force of 0.005" diameter wire

Square flat plate with all edges supported above and below, or below only, and a concentrated load at the center.

$D := \frac{0.1266 F \cdot L^2}{E \cdot t^3}$ Equation 3

$L := 1ft$ Length and base of square plate

$E := 187.5 \frac{kN}{mm^2}$ Modulus of elasticity for stainless steel 302

$D := 0.1in$ Deflection

$t := 0.015in$ Thickness of shim stock

$F := \frac{D \cdot E \cdot t^3}{0.1266 \cdot L^2} = 2.239\,N$ Force required to deflect 0.1in