Swimming Robots Using Memory Metal

Joshua R. Heckman, '23

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Swimming Robots Using Memory Metal

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Spring, 2023
Abstract

While in the very early stages of life, Barnacle nauplii are only a few micrometers in length, which causes them to experience a very low Reynolds number while swimming through water. It is important to understand how these biological creatures swim, so their movements can be mimicked and incorporated into robotics. Currently, there are no autonomous underwater vehicles (AUV) that are capable of carrying out missions in fluids with low Reynolds numbers. This project aimed to replicate the movement of a Barnacle Naupli with the use of muscle memory wire, in hopes that one day a AUV that can operate in low Reynolds numbers will be achieved. This project built off of the work of previous students Hannah James and Eleanor Van Rheenen in collaboration of Biology and Engineering departments at Swarthmore College. The previous projects have analyzed the arm movements nauplii, and explored the characteristics of the muscle memory wire. Using data from the previous research, this project served as an experiment to build a wire holder contraption that was capable of contracting at least 1 inch of wire as well mimicking the range of motion of one of the nauplii arm movements with a rigid oar. While the first attempt at building a wire holder contraption with pulleys was somewhat unsuccessful, the second attempt successfully replicated the range of motion of two of the nauplii arms autonomously using a nitinol spring, a circuit, and a rigid carbon fiber rod.
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Introduction

Biomimicry is the design and production of materials, structures, and systems that are modeled on biological entities and processes. Biomimicry takes inspiration from natural selection solutions which are adopted by nature and translates the principles to human engineering. Scientists and engineers have a lot to learn from biological creatures that have spent millions of years adapting and evolving to their environment. This project seeks to understand how Barnacle Nauplii swim in low Reynolds numbers, and implement a way to mimic their movement using robotics and muscle memory wire.

Crustaceans begin life as an egg and then transition through many larval stages before reaching full size. Barnacles in particular have three stages of life: nauplius, cyprus, and adult. At the end of each stage of life, the exoskeleton is shed which is why the Nauplius looks much different than the adult barnacle. During the first stage of life, the nauplii are less than 1 millimeter in length. The barnacle nauplii have a few features which make them distinguishable from the other stages. The three main features of the nauplius are their appendages on their head (often referred as horns), their tail, and three sets of arms.

One specific type of barnacle is the Tetracita japonica nauplii. The Tetracita japonica nauplii have three sets of arms which move back sequentially, and then return to the swept forward position together. Using this method, the Tetracita japonica nauplii moves in a two step forward, one step back motion in viscous liquids which allows the creature to make forward progress in low Reynolds numbers. This stroke can be compared to a swimmer's arm movements during a cycle of breaststroke. The Tetracita japonica nauplii is only 447.4 micrometers in
length, and swims at a speed of 4.5 millimeters per second. While swimming, the Tetraclita japonica nauplii experiences a Reynolds number of 2.

There will be many applications for robots that successfully mimic the swimming pattern of the Tetraclita japonica nauplii. A robot with the ability to swim at low Reynolds numbers has many underwater applications such as exploration of oceans with high densities. One particular application this project looks into is the exploration of an ocean on one of Jupiter’s moons, Europa. Europa contains an ocean that is a mix between ice and water, causing it to have a high viscosity. Europa’s ocean is of high importance because it is believed to be the most likely place to find life other than earth. As of now, there are no AUV’s that are capable of moving in these slushy conditions, or any liquid that may cause the swimming robot to experience a low Reynolds number. It is important that the movements of barnacle nauplii are studied and are incorporated into robotics so one day we may be able to explore Europa’s oceans.
**Technical Discussion**

**Nitinol Titanium Shape Memory Wire:**

Typically, motors are used to create mechanical movements in robots. However, this project seeks to use Nickel Titanium (Nitinol) shape memory alloys (NiTi SMA) instead. The reasoning behind this choice is that SMA wire is relatively inexpensive compared to electric motors. Furthermore, SMA actuators do not need gearboxes or mechanical subsystems to create linear movement where motors do. If this robot will be operating many millions of miles away from earth, it is important to limit the mechanical systems. Often the more moving parts something has, the more likely it is to have problems or break.

The Nickel Titanium shape memory alloy has two existing crystalline structures that are dependent on temperature. The two crystalline structures, austenite and martensite, give NiTi SMA unique properties that allow it to expand and contract when heat is added or subtracted from the wire. Austenite has a centered cubic structure which makes the molecule very organized. Martensite has less symmetry and either has a tetragonal, orthorhombic, or monoclinic structure. When in the martensite structure, the wire is soft and ductile. As the wire transitions to the austenite structure, it becomes stiff and strong.

![Figure 2. Nitinol’s two crystalline structures, Martensite and Austenite, which are dependant on temperature](image)

When the SMA wire is heated, the wire transitions from the martensite structure to the austenite structure. The temperature at which the transition from martensite to austenite is known as the activation temperature. As the molecules become more organized, this causes the wire to contract or shorten. In this project the SMA wire will control the arm movements of the robot. The wire will either be directly attached to the arm or incorporated in a small mechanical system that pulls the arm in one direction when the wire is heated, then allows the arm to return to its
original position when it is cooling down. However, in order for the wire to return to its original length, a force is required to pull it back into position, such as a spring.

**Tetraclita Japonica Nauplii Arm Analysis:**

Karen Chan, a biologist at Swarthmore College, performed a kinematic and hydrodynamic analysis on the nauplius which focused on the three appendages and how they move during each stroke. Chan was able to graph the movement of the nauplii arms using laser tracking technology.

![Figure 3. Nauplius diagram with angle vs time graph of each appendage for one full stroke](image)

The chart above plots the angle of each of the appendages with respect to time in ms. It is important to note that each of the arms have their own cycle, and do not sweep back at the same time. It appears that the antenna and mandible appendages are very similar in their cycle with about 20 ms delay between the two. The antennule seems to be the opposite, traveling the opposite direction of the antenna and mandule during the cycle. The very end goal of this project is to have a robot that has three appendages that mimic the time vs angle graph above, however, the time scale will need to be adjusted in order for the robot to have the same mobility as the nauplius in low Reynolds numbers.

**Reynolds Number:**

The Reynolds number is a dimensionless quantity that helps predict fluid flow patterns in different situations by measuring the ratio between inertial and viscous forces. The Reynolds number can be expressed with the equation \( Re = \frac{I \cdot U}{v} \) where \( I \) is the length of the object, \( U \) is the
average speed at which the object swims at, and \( \nu \) is the kinematic viscosity of the medium in which the object will be swimming through. In order for the robot to have the same performance as the nauplius, the Reynolds number must match the Reynolds number the actual sized nauplius. This yields the equation \( Re_{\text{nauplius}} = Re_{\text{robot}} \). Organisms that are small, such as nauplii, have a small Reynolds number which puts them in the laminar regime. The robot is designed to swim in a medium with a high kinematic viscosity which also leads to low Reynolds numbers. This reasoning is why Professor Carr Everbach of Swarthmore College selected the Teraclita Japonica Nauplius for this project.

In order for the larger robot to match the Reynolds number of the nauplius, the swimming speed must be adjusted. The swimming speed will be affected by how fast or slow the arms of the robot move through their swimming motion. The speed of the robot must be calculated. By substituting in for the reynolds number and solving for the average speed of the robot, the equation becomes \( \frac{U_{\text{robot}}}{l_{\text{robot}}v_{\text{nauplius}}} = \frac{Re_{\text{nauplius}}v_{\text{robot}}}{l_{\text{nauplius}}} \). Another important equation is the advance ratio: \( J = \frac{U_{\text{nauplius}}}{2\theta f L m} \) where \( \theta \) is the mean appendage amplitude in radians, \( f \) is the beat frequency, \( L \) is the mean appendage length, and \( m \) the number of appendage pairs that contribute towards propulsion (In this case, \( m = 2 \) because it is assumed the antennule appendage contributes very little to the propulsion). The advance ratio compares the larval swimming speed to the speed of the appendage tips. Using the previous calculated \( U_{\text{robot}} \), the appendage speed can be calculated using the equation \( U_{\text{appendage}} = J \times U_{\text{robot}} \). After comparing the appendage speed of the robot to the appendage speed of the nauplius, the timing of the chart can be adjusted so the robot has the same Reynolds number as the nauplius. Although the end goal of this project is only to replicate the range of motion of the nauplius, it is important to recognize that the speed of the stroke must be adjusted in order to match the Reynolds number of the robot to that of the nauplius.

**Circuit Components**

While the circuit for this project is relatively simple, it contains two elements, an Arduino Uno and a MOSFET, that are complex and need to be discussed. The Arduino Uno is a microcontroller board that can be coded to perform specific tasks. The Arduino contains 14 digital input/output pins, 6 analog inputs, a 16 Mhz resonator, a USB connection, a power jack, and a reset button. Of the 14 input/output pins, 6 of them can be used as pulse width modulation (PWM) outputs. This essentially allows the Arduino to produce certain analog quantities by varying the pulse width of a fixed frequency rectangular waveform. The specific pins used in the circuit were pin 12 and pin 8 shown as D12 and D8 in the diagram below. When pin 12 or 8 are high, they emit a voltage of 5 volts.
For this project, an Arduino Uno will work in conjunction with a metal oxide-semiconductor field effect transistor (MOSFET) to control the heating and cooling of the SMA wire. The particular MOSFET used in the circuit is a IRF3709 MOSFET.

The MOSFET is a solid state switch that can act as a gate for current. When in its off state, the MOSFET does not conduct electricity. When in the on state, the MOSFET will allow electricity to pass through to ground. The three pins of the MOSFET shown in figure 5 are the gate, source, and drain. The drain is connected to the load and the source is connected to ground. The gate controls the flow of current from the source to drain by being connected to the voltage source. The gate terminal of the MOSFET will be connected to the PWM output pin of the arduino. When the arduino PWM pin is high, the MOSFET gate allows current to flow from the DC power source through the Nitinol wire to ground, so the SMA wire is heated. When the arduino PWM pin is low, no current flows to the SMA wire, causing it to cool.
Previous Work

When initially deciding on the memory wire, Hannah James tested 4 types of nitinol shape-memory alloys that had different activation temperatures. Each wire was .5mm in diameter and 1 meter long. The activation temperatures were: wire 1 = 30°C ±5°C, wire 2 = 40°C ±10°C, wire 3 = 50°C ±10°C and wire 4 = 70°C ±10°C. In order to reach the activation temperature, current was run through the wire and temperature was measured using a thermocouple thermometer. A summary of the results are provided in the table below.

Table 1. Summary of current required to change the crystalline structure of the Niti SMA

<table>
<thead>
<tr>
<th>Wire</th>
<th>Activation Temperature (°C)</th>
<th>Current required (amps)</th>
<th>Temperature of wire (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30 ±5</td>
<td>.87</td>
<td>36.9</td>
</tr>
<tr>
<td>2</td>
<td>40 ±10</td>
<td>1.12</td>
<td>53.2</td>
</tr>
<tr>
<td>3</td>
<td>50 ±10</td>
<td>1.22</td>
<td>61.0</td>
</tr>
<tr>
<td>4</td>
<td>70 ±10</td>
<td>1.67</td>
<td>83.2</td>
</tr>
</tbody>
</table>

While heating the wires, it was observed that wires 1 and 2 had very little contraction while wires 3 and 4 both contracted about 1 cm. It was decided that wire 3 would be used for this project because it required less amps to contract than wire 4, ultimately saving power. Further experiments were carried out to determine the exact amperage and power required to contract wire 3, and how much force the wire was capable of when contracting. Hannah attached the end of the wire to a spring. When the wire was heated, the displacement was measured and then force was calculated using Hooke’s law: \( F = kx \) where \( k \) is the spring constant in newtons per meter and \( x \) is the change in length of the wire in meters. Table 2 shows the current I, voltage V, temperature T, length of spring L, extension of spring x, and force exerted F.
Table 2. Table showing various measurements when current was applied to wire 3

<table>
<thead>
<tr>
<th>I (A)</th>
<th>V (V)</th>
<th>T (°C)</th>
<th>L (cm)</th>
<th>x (cm)</th>
<th>F (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>21.9</td>
<td>9.50</td>
<td>3.05</td>
<td>1.0922</td>
</tr>
<tr>
<td>0.44</td>
<td>3.11</td>
<td>30.8</td>
<td>9.55</td>
<td>0.05</td>
<td>1.1101</td>
</tr>
<tr>
<td>0.50</td>
<td>3.38</td>
<td>31.8</td>
<td>9.60</td>
<td>0.05</td>
<td>1.1280</td>
</tr>
<tr>
<td>0.56</td>
<td>3.66</td>
<td>34.5</td>
<td>9.60</td>
<td>0.00</td>
<td>1.1280</td>
</tr>
<tr>
<td>0.62</td>
<td>3.94</td>
<td>36.4</td>
<td>9.60</td>
<td>0.00</td>
<td>1.1280</td>
</tr>
<tr>
<td>0.86</td>
<td>4.49</td>
<td>45.2</td>
<td>9.95</td>
<td>0.45</td>
<td>1.2534</td>
</tr>
<tr>
<td>1.04</td>
<td>5.05</td>
<td>48.3</td>
<td>10.15</td>
<td>0.65</td>
<td>1.3250</td>
</tr>
<tr>
<td>1.24</td>
<td>5.60</td>
<td>65.0</td>
<td>10.20</td>
<td>0.7</td>
<td>1.3429</td>
</tr>
</tbody>
</table>

It was determined that the required amperage for wire 3 was 1.24 amps and the power required was 7 Watts, which would be used from here on out when testing the wire. It took 20 seconds for the wire to reach 65 degrees and 35 seconds for the wire to return to its original length.

After the preliminary experiments involving the SMA wire were completed, Hannah moved into a design phase where different setups were contracted to move a lever, representing the nauplii arms. Figure 6 shown below was Hannah’s initial design.

Figure 6. Initial design proving memory wire could be used to move an arm
Experiments were conducted by connecting Crocodile clips coming out from the power supply in turn in order to deliver current and allow for heating. The power supply was turned off when the arm reached maximum displacement and was no longer moving. Compressed air was then used to cool the wire until the lever arm returned to its original position.

Figure 7. Original design performing one full arm stroke

Although this setup resulted in proof that memory wire could be used to move an arm, there were many flaws with the design. The springs were originally intended to help assist the memory wire return to its original position, however, it caused some of the force of the memory wire to be wasted. Instead of using all of the force to move the lever arm, it was wasted on stretching the spring. Furthermore, the spindles were placed in the design to allow more length of the SMA wire to be used in the design in hopes that there would be a greater displacement of the arm. Instead of rotating around the spindle, the SMA wire tightened around the spindle. To put it in simple terms, the design would have had the same displacement without the spindles in the design.

Using the findings from the first design, many improvements were made which resulted in a second design shown in figure 8. In the second design, the spindles and springs were removed and replaced with a zig zag formation and pulleys. Since the pulleys had a smooth surface, the memory wire was able to rotate around them while contracting. A slimmer arm was also implemented into the second design. The length of each SMA wire was 1.23 meters and the length of the lever arm was .36 meters.
Figure 8. The second design which replaced the spindles and springs with a zig zag formation and pulleys

The wires on the left shown going out of the image in figure 8 were attached to a breadboard and an arduino. This meant the experiment would be fully autonomous. The wires were alternated in heating. One wire was heated for 20 seconds, then there was a 10 second pause, then the other wire was heated. From the tip of the arm, the total movement was 1.5 cm from the original position with an angular displacement of 4 degrees.

Figure 9. One full arm stroke of the second design

At this point in the project, Hannah’s work was completed and Eleanor Van Rheenen had picked up the project. Eleanor performed further tests on the memory wire to determine how much it pulls, how hard it pulls, and whether the bending stiffness is important. Eleanor was able to determine the wire contracts to 95.38 percent of its length in 10 seconds and that the wire was able to lift masses of over 1 kilogram, which is plenty for the purpose the memory wire serves in this project.

Eleanor then focused her attention on how to configure the wire so that she could fit a lot of wire into a small space. During the design process, she determined the constraints for the wire holding structure. The wire could not overlap itself, it must be able to move easily, the structure
must be sturdy enough to harness wire movement, and the structure's material could not be conductive. Eleanor was able to design and test one prototype shown in figure 10.

![First prototype of structure capable of holding memory wire](image)

Figure 10. First prototype of structure capable of holding memory wire

The first prototype did not perform as expected. There was too much friction for the memory wire to move easily through the holes. Also, the holes were too close together and the wire overlapped in some cases. The findings from Hannah and Elaenor’s past designs will help with future design of the wire holder and mechanical system for this project.
ABET Requirements:

Project Constraints

The success of this project is contingent on many factors, however, time seems to be the largest constraint. This was an ongoing project that has been in development for over a year now, so the main focus was to help this project come closer to the final product. When this project is completed several years from now, The hope is that there will be a working autonomous swimming robot that mimics the movement of a barnacle nauplii, and is able to swim in fluids with a high kinematic viscosity. Since only 5 months were allotted to complete this project, time was the largest constraint in making this project successful. However, breaking the work down into smaller goals allowed the success to be measured throughout the process.

Another constraint was the materials and manufacturing capabilities of the Swarthmore machine shop. The contraption to hold the SMA wire was manufactured in the machine shop. Aluminum was the main material available and it was machined using the HAAS Mini Mill.

Project Requirements

In order for this project to be truly successful, two main tasks had to be accomplished. The first task was creating a contraption to organize and hold the memory wire. The contraption's success was measured by how far the end of the wire moves when a current is applied, and whether it could fit in a fist sized robot. The dimensions of the “fist sized” robot were constrained by a 3d printed oval shape, which had a length just over 4 inches and a width of 3 inches. The design goal for this contraption is to have a contraction of at least 1 inch which would be measured by hanging a weight from the memory wire measuring the contraction using a tape measure in the background.

The second task was mimicking the arm movement of the barnacle nauplii with an autonomous mechanical arm controlled by the memory wire. In order for this task to be successful, the movement of the arm must have the same range of motion of the nauplius arms seen in figure 3. This task will be successful as long as the range of motion of one of the arm movements can be properly mimicked. When testing the mechanical arm, the range of motion was drawn on a piece of papers using the angles from figure 3. If the mechanical arm was able to autonomously move back and forth to the extremes, the project was deemed successful.

Professional Standards/ Codes

This project does not have to follow any professional standards or codes. Since this is a new technology that has not been previously worked on, no standards were able to be found.
Designs

Initial Wire Holder:

A lot was learned from Hannah and Eleanor’s previous experiments and designs. While designing the contraption to hold the memory wire, the zig-zag formation was integrated with pulleys. This technique had the capability to fit a lot of memory wire in a small space without sacrificing the ability of the memory wire to move freely.

![Design drawings for initial wire holder design](image)

This design featured ceramic pulleys in order which allowed the SMA wire to cool faster. Previous designs incorporated metal wheels which conducted the heat, causing the wire to stay contracted for a longer time. The goal of this wire holder was to be able to hold 3 different sections of wire that were each 24 inches long. If the contraption worked properly and the memory wire contracted to 95% of its original length, this would allow about 1.2 inches of contraction for each section of wire. The three separate sections could be used to control individual arm movements of the nauplius.
Figure 12. Computer aided design (CAD) drawings of initial wire holder

The final design was generated using Fusion 360, a computer aided design program. Each element of the wire holder was designed in its own file, then each part was inserted into an assembly to join the parts together.

**Rigid Arm Mechanism:**

After designing a holding contraption for the SMA wire, the contraption to mimic the range of motion of the nauplius arms was thought out.

![Graph showing total movement of all three arms](image)

Figure 13. Expanded graph showing the total movement of all three arms in terms of angle and time

To successfully mimic the movement of the nauplii, there are three main topics that have to be addressed: how far the arm must move, the geometry required to recreate the motion, and the timing of the movement. This project focused on getting the correct amount of angular motion and the geometry of the system. The first design incorporated the wire holder contraption, a power source, a spring, a rigid arm of an arbitrary length, and a pivot point.
To simplify the design of the memory wire nauplius robot, the limbs will be represented by a straight, rigid oar made from a carbon fiber rod that can pivot about a fulcrum. The part of the oar to the right of the fulcrum in the diagram below represents the arm of the nauplii that is moving through the liquid, while the part of the oar to the left of the fulcrum will be attached to the memory wire. One cycle of the nauplius stroke can be broken down into two components: the power stroke and the recovery stroke. In this model, the power stroke will occur when the power source is turned on and the memory wire contracts to 95% of its original length. Whereas the recovery stroke happens as the power source is turned off, causing the wire to cool and return to its original length. A spring is added to the design in order to aid the arm to return to its original position. From previous experiments, it has been determined that the pulling force from the memory wire is strong enough to overcome the restoring force from the spring throughout the power stroke.

Figure 14. Rigid Arm Mechanism that integrates wire holder design

Figure 15. Geometric relationship between the angle of nauplius arm movement, that, the length of the moment arm, and the contraction of the wire, d.
Since each arm has its own stroke that varies in degrees, the length of the moment arm for each set of arms will be different. In figure 15, theta represents the total angle of the complete stroke, \( d \) represents the distance the memory wire contracts, and \( L \) of moments arm represents the distance from the fulcrum to the connection between the memory wire and rigid oar. Using simple geometry, the length of the moment arm can be determined: 

\[
\ell_{\text{moment arm}} = \frac{d}{\tan(\theta)}.
\]

Using the contraption above, the arm movement of the nauplii should be able to be replicated. The timing and speed of the arm will be controlled by the heating and cooling of the wire. If the arm needs to move faster, the current through the nitinol wire will be increased. However, increasing just the current through the wire will only increase the speed of the power stroke. In order to increase the speed of the recovery stroke, there are two things that can be done. If the wire has some sort of cooling mechanism, such as a fan or a heat transfer system, the wire will go back to its original length faster then if it were just left there to cool. Also, the restoring force contributes to the speed at which the arm recovers. The significance of the restoring force will be shown through a series of tests in the testing section below. Since this project primarily focused on matching the angular motion of the robot to that of the nauplius, the speed at which the arm moved was ignored.

**Double Spring Mechanism:**

After an unsuccessful test of the wire holder contraption design described in the Manufacturing and Testing section below, a new design had to be thought out.

![Double Spring Mechanism](image)

**Figure 16.** Drawing of Double Spring Mechanism that includes a power source, breadboard, and arduino for autonomous operation
After some preliminary research, it was decided Nitinol springs would be used to try to create the arm movements. The helical design of springs allows it to have more contraction than a straight wire. The spring would also serve as a restoring force for the oar when stretched. Using two springs, one on each side, guarantees more control over the arm than the original design. After figuring out the correct timing of applying current through the top and bottom springs, the oar would be able to accurately mimic the motion of the nauplius arms. If a hinge was added in the middle of two arms, this contraption would be able to move a set of arms simultaneously.

**Autonomous Circuit Design:**

![Circuit Diagram](image)

*Figure 17. Circuit designed to control flow of current through top and bottom spring*

In order to make the arm mechanism autonomous, there needed to be a way to control the current that flowed through the top and bottom nitinol springs. The circuit shown above uses a DC regulated power supply which is a BK Precision 1670A. Other elements included in the circuit are four 1kΩ resistors, two LED lights, two IRF3709 MOSFETs, and an arduino uno r3. The arduino uno is connected to each of the MOSFETs through pin 12 and pin 8. These are PMN analog outputs that produce 5 volts when they are high and 0 volts when they are low. The MOSFETs act as a switch. When the arduino pin is high, the connected MOSFET allows current to flow through the nitinol wire causing it to contract. The LEDs connected in parallel with the nitinol wire act as a visual representation when current flows through that portion of the circuit. The arduino uno is powered through a usb connection to a computer. Not only does the usb connection deliver power, but it also uploads code to the arduino that switches when pin 12 and 8 are high or low.
Manufacturing and Testing

Manufacturing of Initial Wire Holder Design:

After completing the initial wire holder design in fusion 360, the manufacturing feature was used to create toolpaths. Fusion 360 allows the toolpaths to be exported as g-code onto a usb drive which could be inserted and interpreted by the HAAS Mini Mill that would execute the toolpaths.

Figure 18. Image of HAAS Mini Mill in Swarthmore machine shop

The pieces of stock used to manufacture the wire holder structure were two 1”x1”x2” pieces of aluminum and a 10 inch long ball grooved aluminum rod. First, the necessary toolpaths were created for the top of the wire holder.

Figure 19. Toolpaths generated in Fusion 360 for the top half of the aluminum piece

The facing operation created a smooth finish on the top of the stock using a facing tool. The 2D pocket operation was used to mill out the 5 rectangular pockets using a ⅜ inch diameter tool. The last operation for the top of the face was a contour around the perimeter of the stock. This contour ensured the rectangular piece had the correct dimensions.
Figure 20. Image of Aluminum piece after the top half toolpaths were performed in HAAS Mini Mill

The drilling operation was used to remove a small amount of material to mark where the through hole would be made. Using a manual drill press, the through holes on the top face would be completed. One of the aluminum pieces was drilled into with a tap to create threads in which the grooved aluminum rod would be inserted. The other aluminum piece would be held in place using 4 nuts shown in figure 24.

Figure 21. Image of drill press being used to create holes through the top of the aluminum pieces

The only operation for the bottom face was a facing operation. The facing operation made the aluminum stock to the correct thickness.

The ceramic pulleys would rotate about a carbon fiber rod that was inserted through the side of the stock, so holes through the side of the aluminum had to be milled.
A spot drill operation was used to mark the location of each hole, and was then followed by a peck drill operation. A peck drill operation was used to ensure the aluminum shavings could escape and so that extreme heat and stresses on the tool itself were avoided.

The wire holder was then assembled after cutting the 10 inch grooved rod into four 2.5 inch sections.

While machining of the aluminum parts was ongoing in the HAAS, J. Johnson, the machine shop specialist, manufactured the ceramic pulleys. Machinable ceramic of $\frac{3}{8}$ diameter
was ordered from McMaster-Carr. In order to make the ceramic pulleys, J used a lathe to first shave the diameter down to \( \frac{1}{4} \) inch. Using a \( \frac{1}{2} \) millimeter grooving tool, J made grooves in the wheels so the wire would have a track to follow. Using the same grooving tool, J separated the pulleys so they each had a thickness of about .2 inches.

![Figure 25. Images of ceramic rod being machined into \( \frac{1}{4} \) in pulleys using a lathe and grooving tool](image)

After 20 ceramic pulleys were manufactured, the rest of the wire holder was assembled. Carbon fiber rods that were cut into 1 inch sections so they could be inserted into the holes of the sides of the aluminum. After cutting the carbon fiber rods into small sections with a miter saw, there was a significant amount of fraying near the edges shown in figure 26. There was a concern the fraying may increase friction when the ceramic pulleys rotated around the rod, so fiberglass resin was applied to each carbon fiber section.

![Figure 26. Image showing fraying occurring on the edges of carbon fiber section](image)

After the resin had dried and the fraying on the carbon fiber was reduced, they were inserted into the aluminum sections and two pulleys were placed on each section for initial
testing. It is important to note that the wire holder could accommodate more than 2 pulleys in each carbon fiber rod, however, the ceramic pulleys took a significant amount of time to manufacture so a total of 20 pulleys would suffice for initial testing.

Testing of Initial Wire Holder:

Two different types of wire were tested on the wire holder: .5 mm diameter wire and .3 mm diameter wire. For each of the wires, 24 inches of wire were placed around the pulleys and connected to a hanging weight shown in figure 27.

Figure 27. Wire holder testing apparatus

The contraction of the wire was measured using a tape measure as a reference. The starting position of the weight was marked on the tape measure, and after contraction the total displacement was measured. To contract the wire, the power source was turned on and the current was increased from zero until the wire started to contract. After the wire had contracted, the power source was turned off and the wire would return to its original position after it cooled. During the initial tests, a 100 gram weight was tied to the end of the wire. The first wire tested was the .5 mm wire. Unfortunately, there was no contraction when using the .5 mm diameter wire. The wire was hot enough to contact because there was smoke coming off of it around 3 amps. The .5 mm wire was swapped out for the .3 mm wire. The .3 mm diameter wire had a
contraction of .5 inches at just over 1 amp. However, the 100 gram weight took a very long time to pull the wire back to its original length. A weight of 300 grams was tied to the end of the wire, and then the contraction was measured once again using the same current. I found that the .3 mm wire contracted the same amount, but took significantly less time to return to its original position. Since this did not meet the design requirement of a minimum contraction of 1 inch, research was performed and a new design was implemented shown in figure 16.

**Initial Spring Tests:**

After ordering two Nitinol 2-way memory coil springs from Nexmetal, similar contraction tests were done. The springs had a .75 mm diameter wire, and a length of 1.97 inches. A 300 gram weight was hung from the end of the spring, and the power source was turned on. Current was slowly increased until a contraction occurred. The spring contracted a total distance of 1.25 inches at 2.6 amps.

Table 3. Displacements of wire when tested in wire holder and initial spring displacement test

<table>
<thead>
<tr>
<th>Test Subject</th>
<th>Weight Attached (grams)</th>
<th>Current (Amps)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Holder w/.5mm d wire</td>
<td>350</td>
<td>1.52</td>
<td>0</td>
</tr>
<tr>
<td>Wire Holder w/.3mm d wire</td>
<td>350</td>
<td>1.02</td>
<td>.5</td>
</tr>
<tr>
<td>Spring .75mm d</td>
<td>350</td>
<td>2.6</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Once successful testing of the spring was completed, the double spring design was implemented with a rigid carbon fiber oar and pivot point. During the first test, each spring was placed within the limits of the robot's dimensions.
A 2.6 amp current was applied to one of the springs. The spring contracted, however, there was not much movement in the oar. Another test was performed with the springs pretensioned, meaning that they were placed further away and stretched more. Figure 29 showed this pretension method caused the oar to have a greater range of motion than the previous non-tensioned test. The ground of the power source was connected at the connection point of the springs and the oar. Each spring had its own “hot” wire that was connected at its endpoint. The current flowing through the nitinol springs was changed from the top spring to the bottom spring in intervals by manually unplugging and plugging in the respective wires to the positive terminal of the power source repetitively. This caused the carbon fiber rod to swing back and forth with about a 45 degree range of motion. Although this wasn’t the perfect range of motion needed to match the nauplius arm, it was a promising start.
With a few adjustments to the length of the moment arm, the oar theoretically should be able to move through the entire range of motion of the antenna. The antenna is the middle set of arms in the nauplius that travels through the largest range of motion, which is about 85 degrees marked by the pencil lines on the paper in figure 29.

**Circuit Integration:**

Once the double spring mechanism proved it had the ability to mimic the nauplius arm movement, it was time to integrate a circuit that allowed the oar to move autonomously. The circuit in figure 30 was built on a breadboard and connected to an arduino, the power source, and the nitinol springs.

![Image of single spring design with autonomous circuit integrated](image.png)

Figure 30. Image of single spring design with autonomous circuit integrated

Instead of using the two spring mechanism, one spring was stretched across the length of the robot's dimensions. This allowed the spring to be pretensioned while also fitting the requirement of fitting in a fist sized object. Code was written in an arduino sketch in order to control pins 8 and 12 of the arduino. The coding language used was C++. 
const int top_spring = 12; // pin 12 on arduino associated with top spring
const int bottom_spring = 8; // pin 18 on arduino associated with bottom spring

void setup() {
    pinMode(top_spring, OUTPUT);
    pinMode(bottom_spring, OUTPUT);
    pinMode(LED_BUILTIN, OUTPUT);
}

void loop() {

digitalWrite(top_spring, HIGH);
digitalWrite(bottom_spring, LOW);
digitalWrite(LED_BUILTIN, HIGH); // turns LED on arduino on
delay(20000); // top spring current is turned on for 20 seconds
digitalWrite(top_spring, LOW);
digitalWrite(bottom_spring, LOW);
digitalWrite(LED_BUILTIN, LOW); // turns LED on arduino off
delay(20000); // no current through top or bottom spring allows top spring to cool for 20 seconds
digitalWrite(top_spring, LOW);
digitalWrite(bottom_spring, HIGH);
digitalWrite(LED_BUILTIN, HIGH);
delay(20000); // bottom spring is turned on for 20 seconds
digitalWrite(top_spring, LOW);
digitalWrite(bottom_spring, LOW);
digitalWrite(LED_BUILTIN, LOW);
delay(20000); // no current through top or bottom spring allows bottom spring to cool for 20 seconds
}

Figure 31. Code written in arduino sketch to control current flow to the spring

Altering the timing of the delay function will directly affect how long each spring will contract or cool for. In the code above, the top half of the spring was fed current for 20 seconds, then no current was fed through either the top or bottom half of the spring. After the 20 second resting period, current was fed through the bottom half of the spring for 20 seconds, then no current was fed through the top or bottom half of the spring. The code was in a loop, meaning this sequence of events would continue to happen as long as the code was still uploaded to the arduino through the usb. It is important to note that the length of the moment arm also played an important role in the range of motion of the rigid oar. When the moment arm was at its original placement, the rigid arm only had a range of motion of 45 degrees, which mimicked the antennule on the nauplius.
Figure 32. Carbon fiber oar moving autonomously through the range of motion of the nauplius’ antennule

The moment arm was decreased to about half of the original length, and the oar had a range of motion which mimicked the antenna.

Figure 33. Carbon fiber oar moving autonomously through the range of motion of the nauplius’ antennule

It was important that both of these sets of arms could be mimicked, so that eventually a final design can be incorporated that allows the three sets of arms to move through their respective range of motion simultaneously.

**Double Arm Test:**

The last goal of this project was to have one spring autonomously control one set of arms. Two carbon fiber rods were connected with a flexible heat shrink wrap that could act as a hinge in the middle. The hinge of the arms could be connected to the center of the one spring design to
move up and down. This would cause each arm in the set to go through a symmetrical motion about the center line. Using the same code in figure 31, the double arm test was performed.

Figure 34. Image showing successful autonomous double arm test
Discussion

In this discussion, an analysis of each of the mechanisms designed and built will be addressed. The first design of the project was the wire holder. The wire holder was designed to hold 3 pieces of wire that were each 24 inches in length, and its overall dimensions were 2”x1”x1”. The dimensions were small enough to fit in a fist sized object which cleared that design goal. Under optimal conditions, the wire would contract to 95% of its original length, and the design goal of minimum contraction of 1 inch would have been achieved. Unfortunately, when testing both the .5mm and .3mm wire, neither of them reached the design goal. When the .5mm wire was tested, there was no contraction at all. It was known the wire reached activation temperature because the current was increased until smoke was coming off the wire. This indicated that the wire became hot enough to burn the oils that existed on it.

There were a number of reasons that may have caused the wire holder to underperform. The first being the characteristics of the wire when it is heated. As the nitinol wire transitions to its austenite phase, it becomes stiff and rigid. When it enters this phase one could imagine it becomes difficult to freely move over a pulley. For example, a steel rod would have an incredibly hard time rolling around a pulley unless a very large force was applied that would deform the rod. However, the larger the pulley is, the easier it would be to rotate the steel around it. It is suspected that Hannah James originally had success with pulleys because they were large and had more spacing between them. However, there must be a certain threshold at which the nitinol wire can not rotate around pulleys because it becomes too stiff when heated. The ¼ inch ceramic pulleys simply did not fall in that range for the .5mm diameter nitinol wire. However, the .3mm diameter nitinol wire did have some success when tested using the initial wire holder.

The 24 inches of .3mm wire contracted by a total amount of .5 inches. Although it did not meet the design goal, there are a couple takeaways from this test. One of them being that the wire becomes more flexible and malleable as the diameter decreases. This might be common knowledge for most wires, but proving that the malleability of the austenite phase increases as the radius decreases for nitinol wires is important to understand for future use of nitinol wire. There are a couple other reasons that are suspected why the .3mm diameter wire did not contract to its intended length. One reason may be that the .3mm diameter wire does not contract to 95% of its original length. It was unclear whether Eleanor tested .3mm wire as well as .5mm wire. If the .3mm wire did not contract as much as the .5mm wire, more wire would have been required in order to reach the 1 inch contraction design goal. Another speculation is that the friction between the ceramic pulley and the carbon fiber rod may have been too much for the nitinol wire to overcome completely. The ceramic pulleys were designed so that there would be a slightly larger inner diameter so it could freely rotate around the carbon fiber rod. After adding fiberglass resin to the carbon fiber rod in order to reduce fraying, the diameter of the carbon fiber rod increases slightly. This increase in diameter may have caused too much friction between the carbon fiber rod and the ceramic pulleys as they were trying to rotate.

A number of things could have been designed differently about the wire holder in order for it to perform better, but I think the most limiting factor is the diameter of the pulley and the length of the wire. Increasing the diameter of the pulley would have allowed the nitinol wire to rotate around it easier, however, it also would require a larger design. Similarly, if more .3mm wire would have been required to reach the design goal, the device would have had to be increased. Since this wire holder must fit inside the
robot dimensions, a new contraction mechanism had to be thought of which led to the double spring mechanism.

After tests showed that a singular nitinol spring contracted over an inch, it was decided the springs would be used for the final design. During the initial testing of the double spring mechanism, it was found that the spring had to be pretensioned in order for the spring to contract a maximum amount. According to NexMetal, the nitinol spring could pull with a force of up to 300 grams. With a 300 gram weight attached to the nitinol spring, the total length was just under 4 inches. Since the length of the robot was 4 inches, only one spring was needed to span the length. According to geometry shown in figure 15, a contraction of 1.25 inches would require a moment arm to mimic the antenna of .11 inches, and the required moment arm to mimic the antennule was 1.25 inches. The mandible arm of the nauplius was not mimicked, but it would require a moment arm of 1.05 in if it were. Although these numbers created a starting point, the actual moment arm length was found through trial and error. Using the moment arm lengths above, slight adjustments were made to the length and timing of current applied to the nitinol wire. This resulted in a successful test for the range of motion of the antennule and antenna.

One full set of arms was also able to move back and forth using a hinge between them. Although a full set of arms were not made to mimic a specific arm movement of the nauplius, the previous tests using only one arm proved it is possible.
Conclusion and Future Work

This project served as an experiment to figure out whether it was possible to autonomously mimic the range of motion of the nauplius’ arm movements in a fist sized robot using nitinol wire as the source of motion. In order to do this, a wire holder had to be created that would hold a sufficient amount of wire to contract a minimum of one inch. This contraction of wire then had to be implemented in a mechanism that moved a rigid oar. Using a nitinol spring, a rigid carbon fiber rod, and a circuit, the range of motion for the antennule and antenna arms of the nauplius were successfully mimicked.

Although this project proved that it was possible to use nitinol as a source of motion, there is a lot of work left to be done in order to create a fully functional swimming robot capable of operating in low Reynolds numbers. There are too many steps left to complete in order to complete the full robot, so only the next steps in the near future will be covered in this section. First of all, the speed at which the rigid oar moves must be determined by matching the Reynolds number of the robot to the nauplius. After that, a three dimensional analysis of the nauplius arms must be performed. So far, the angle of the arms has only been measured in one plane. The stroke of the nauplius is more complex and needs to be analyzed perpendicular to the plane that has already been studied. From there, a new mechanism must be developed that will keep the previous range of motion from this project, and add the new movements found from the three dimensional analysis. Also, the arms need to be able to operate with a portable battery source. The next step would be replacing the DC power source with a 9 volt battery that will supply the current to the nitinol wire. In conjunction with that, the usb cable connecting the arduino to the computer will also need to be replaced with something portable. Lastly, the hydrodynamics of the autonomous oar will need to be tested. If the carbon fiber rod is replaced with a more realistic material that better represents the nauplius arm, the arm can then be tested in corn syrup to establish the hydrodynamic performance in low Reynolds numbers. Overall, this project was successful in determining the use of a nitinol wire spring as a mechanism to move a rigid arm, but there is a lot of work that needs to be done in order to create a fully functional autonomous robot that has the ability to navigate Europa.
References


