Fabrication and Testing of Artificial Muscles Created from Fishing Line and Nylon Thread

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1 Abstract

This study investigates the fabrication and testing of artificial muscles utilizing affordable and accessible materials: fishing line and nylon thread. Creating these muscles involves coiling and thermal annealing techniques to create cost-effective actuators. By thermally actuating these muscles with a heat gun, the predicted displacement is achieved. Theoretical expectations, based on mathematical models, are compared against experimental results to assess performance. The findings of this study indicate these homemade artificial muscles to be a promising alternative to mainstream options.

2 Introduction

Artificial muscles are actuators frequently used in the realm of robotics. There is growing value in artificial muscle research, from pneumatic artificial muscles, to electroactive polymers, to shape memory alloys. A majority of this research is conducted by large corporations and is not accessible or affordable for everyday use. An exception to this is artificial muscles fabricated with fishing line and sewing thread.

The goal of this project is to create cost-effective artificial muscles using monofilament fishing line and silver-coated nylon sewing thread without the use of major machinery. The fabrication process will consist of a combination of coiling and thermal annealing techniques. Demonstrating the accessibility of creation and utilization of these muscles through the use of easily obtainable objects is the foremost objective. By comparing their performance and functionality to the expected mathematical models, this project aims to demonstrate how these homemade artificial muscles are a valuable alternative to conventional artificial muscles.

3 Theory

3.1 Theory of Operation

Creating artificial muscles does not require large industrial machines or an in-depth knowledge of materials or mechanics. By creating these muscles in an at-home setting and comparing their performance to predicted mathematical values, it will determine whether these inexpensive homemade artificial muscles are a viable option.

The function of the artificial muscles relies on the coiling of the thread. As the muscle is thermally actuated, the material undergoes thermal expansion, causing the angle between each individual coil decreases. This leads to a compression of the muscle and a displacement of the attached weight from its original position at ambient temperature.

For this project, the artificial muscles will be actuated using a heat gun, creating a change in temperature of the coil. This thermal change will cause the coil to contract.

3.2 Mathematical Theory

To induce a displacement of the artificial muscle, the coil must be thermally actuated. This is done by heating the filament.

The position of the coil, $x(t)$, can be determined by the differential equation[1]:

$$m\ddot{x} - mg + b\dot{x} + \frac{x - x_0 + f_{12}\tau}{f_{11}} = 0 \tag{1}$$

Where m is the attached mass, b is a damping coefficient obtained experimentally, x_0 is the initial position of the end of the muscle, and f_{11} and f_{12} are defined as:

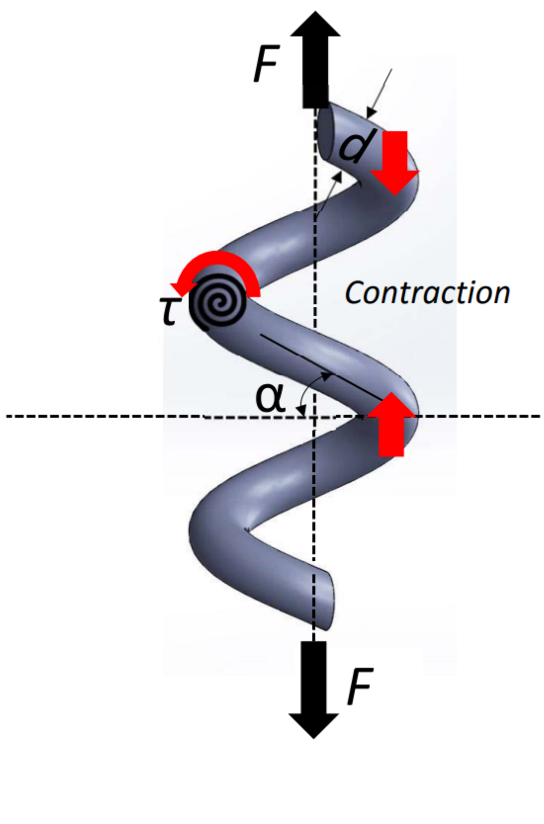
[1] A. Abbas and J. Zhao, "A physics based model for twisted and coiled actuator", 2017 IEEE International Conference on Robotics and Automation (ICRA), Singapore, 2017, pp. 6121-6126, DOI: 10.1109/ICRA.2017.7989726.

$$
\begin{aligned}
f_{11} =& \frac{8n}{\pi^3 d^4}\left(\frac{l}{n}\right)^3 \frac{\cos^4\alpha}{G} + \frac{8n}{\pi d^2}\left(\frac{l}{n}\right)\frac{\cos^2\alpha}{2G} \\
&+ \frac{8n}{\pi^3 d^4}\left(\frac{l}{n}\right)^3 2\sin^2\alpha\cos^2\alpha\frac{1}{E} + \frac{8n}{\pi d^2}\left(\frac{l}{n}\right)\frac{\sin^2\alpha}{2E}
\end{aligned} \tag{2}
$$

$$
f_{12} = \frac{8n}{\pi^2 d^4}\left(\frac{l}{n}\right)^2 \frac{\cos^2\alpha}{G} \tag{3}
$$

Where α is the current pitch angle, n is the number of turns in the coil, l is the length of coil, E is Young's Modulus of the thread, and d is the diameter of the twisted fiber, defined as:

$$
d = d_0(1 + \rho\Delta T) \tag{4}
$$



The temperature induced torque, τ, can be found using the specific form of Hooke's law $\sigma = G\gamma$ where $\sigma = \frac{16\tau}{\pi d^3}$ and $\gamma = \frac{\phi_0(d-d_0)}{2l}$[1]:

$$\tau = \frac{G\phi_0 d^3(d-d_0)}{32l} = \frac{G\phi_0\pi d_0^4(1+\rho\Delta T)^3\rho\Delta T}{32l} \tag{5}$$

Where G is the shear modulus, ϕ_0 is the initial twist angle, d_0 is the initial diameter of the fiber, ρ is the transverse coefficient of thermal expansion, and ΔT, the change in temperature, is the only unknown.

We can define a constant q to be:

$$q = \frac{G\phi_0\pi d_0^4}{32l} \tag{6}$$

Expanding τ, we get:

$$\tau = q(\rho\Delta T + 3\rho^2\Delta T^2 + 3\rho^3\Delta T^3 + \rho^4\Delta T^4) \tag{7}$$

This then gives the differential equation:

$$m\ddot{x} + b\dot{x} + \frac{1}{f_{11}}x = mg - \frac{f_{12}}{f_{11}}q(\rho\Delta T + 3\rho^2\Delta T^2 + 3\rho^3\Delta T^3 + \rho^4\Delta T^4) \tag{8}$$

If there is no movement in the x position, the equation simplifies to:

$$x = f_{11}mg - f_{12}q(\rho\Delta T + 3\rho^2\Delta T^2 + 3\rho^3\Delta T^3 + \rho^4\Delta T^4) \tag{9}$$

At ambient temperature with no mass attached to the coil, x would be:

$$x = f_{11}mg \tag{10}$$

[1] A. Abbas and J. Zhao, "A physics based model for twisted and coiled actuator", 2017 IEEE International Conference on Robotics and Automation (ICRA), Singapore, 2017, pp. 6121-6126, DOI: 10.1109/ICRA.2017.7989726.

4 Methods

4.1 Muscle Construction

To fabricate the artificial muscles, 0.35mm monofilament nylon fishing line and Shieldex® 117/17 silver-coated nylon sewing thread was used. Each thread was be cut to 19 centimeters in length. To secure the two materials together, each set of ends was tied to large paper clips. The thread was then coiled by attaching one of the ends to a drill chuck while the other was held in place so the threads were taught. The drill was spun until the threads were fully coiled together.

Figure 1: Example of a constructed artificial muscle.

After the coils were created, they needed to be thermally annealed. To do this, they were baked on a modified baking tray with screws drilled in on both ends of the sheet. There were be two steps in thermal annealing process. Each bake used a different baking sheet with different placements of the screws.

The first baking sheet had the screws drilled into a position where the coils would be stretched to approximately 10% more than the equilibrium length. The estimated length of the coil was two thirds the original length of the thread. This means the coils were predicted to be approximately 12 centimeters. This meant the screws would have a distance between them of 13.2 centimeters.

Figure 2: Blueprint of 10% stretch baking sheet

The second baking sheet had screws positioned to create a stretch 33% more than the equilibrium length. The screws were set 16 centimeters apart.

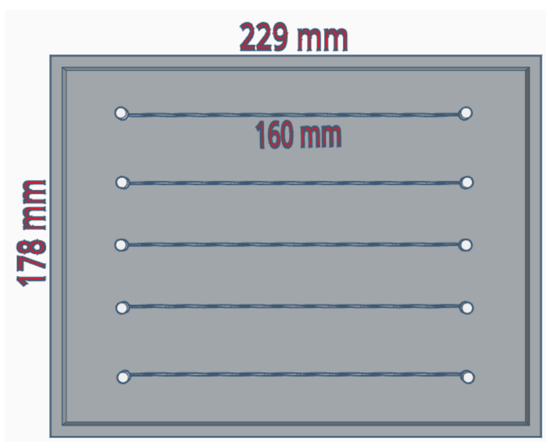


Figure 3: Blueprint of 33% stretch baking sheet

With the baking sheets assembled, the annealment process could begin. First with the baking sheet of 10% stretch, the coils were secured to the screws on both ends. The baking sheet was be placed in an 180 degree Celsius home oven for one hour. The sheet was then removed from the oven and left to cool to room temperature for one hour. The process was then be repeated, but with the 33% stretch baking sheet. The coils were be attached in the same fashion and baked at the same temperature and time. Once the coils have cooled for the second time, the thermal annealing was complete. This process of stretching and heating the muscles would ensure they set and hold their shape.

4.2 Suspension Apparatus Construction

To test the artificial muscles, a suspension system was required. The coil needed to be suspended from a stand with space for a ruler to hang behind it. All the materials of the apparatus also had to be heat resistant, as to prevent the formation of smoke or fire when using the heat gun.

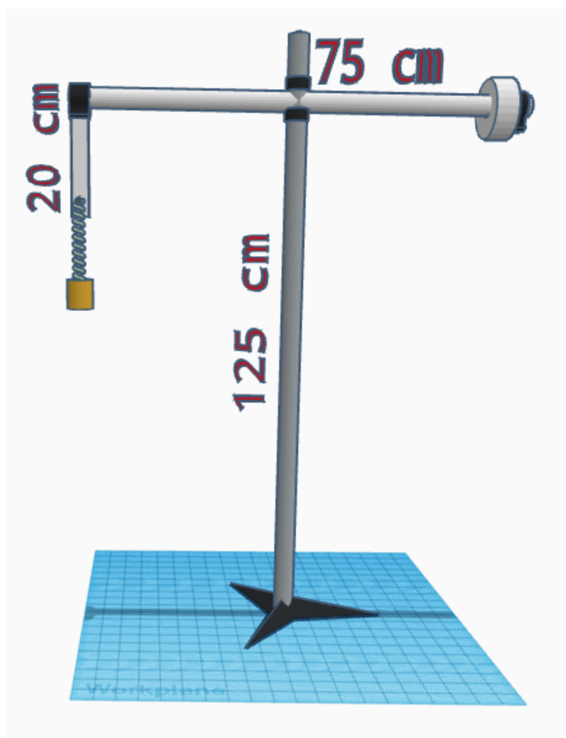


Figure 4: Blueprint of the testing apparatus

4.3 Testing

To verify the function of the muscles and the suspension system, they were first tested without any added mass. The muscle was heated using a heat gun set to 170 degrees Celsius for approximately 30 seconds. The temperature and displacement of the coil was then measured.

Once the functionality of the muscles and the suspension system was verified, testing with a hanging mass began begin. The muscles were tested with hanging masses of 10g, 20g, 30g, 50g, and 100g. They were put through the same process as the massless phase: blasted with a heat gun at 170 degrees Celsius for 30 seconds. The temperature of the coil and displacement measurements were taken each time.

5 Results

To analyze the data collected from experiment, a curve fit was used. To account for any uncertainties, R-squared and mean squared values were calculated during fitting. The R-squared value came out to 0.899 and the mean squared error was 0.124.

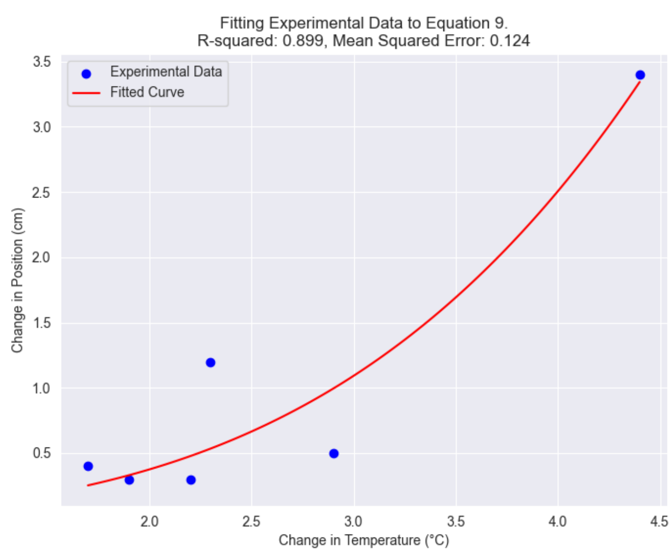


Figure 5: Experimental data fit to equation 9.

6 Discussion

The results gained from testing showed a trend similar to what is expected from the mathematical model. Further testing would be beneficial to reduce the mean squared error and to increase the R-squared value.

There were some setbacks during this project. The original plan was to thermally actuate the muscles using electrical current. This proved to be ineffective, so the heat source was changed to a heat gun for a more direct approach. With using the heat gun, the silver-coated nylon thread was no longer needed. However, the muscles had already been created with the nylon thread in them and did not impact the results. If further investigation was done on this subject, the nylon thread should be omitted unless the goal is to thermally actuate it using electricity.

7 Bibliography

Carter S. Haines, *et al.* "Artificial Muscles from Fishing Line and Sewing Thread", *Science 343*, **868-872**, (2014). DOI: 10.1126/science.1246906.