Multi-Disciplinary Senior Design Conference
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York 14623

Project Number: P09029

Air Muscle Artificial Limb

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ABSTRACT

This project was the fourth iteration of projects using McKibben air muscles to simulate human motion for a robotic arm. The long term goal of these projects was to create small and large scale robotic arms with human dexterity and ranges of motion for intuitive control. Prior iterations focused on overcoming design challenges of the hand and fingers. This iteration focused on creating a prototype and computer simulation of the elbow that can predict the movements of a prototype before having to build it. The computer model took input from LabVIEW, the controlling program, in the same manner as a physical prototype. A prototype of the elbow was built to test and refine the computer simulation. A mathematical model of the pressure in the air muscle was developed, and a mathematical model of the force caused by the pressure was used. The results were output to SolidWorks COSMOS Motion for an animated simulation. The completed project provided the customer with a validated design as well as a design methodology that can be used in support of future project phases.

INTRODUCTION

This project was a fourth in a family of projects to create a robotic arm using the McKibben air muscles. McKibben air muscles consist of a soft inner material (such as surgical tubing) covered in a mesh that was not stretchable. When the inner tubing was pressurized it expands mostly in a radial fashion. Because the outside mesh does not stretch, the length decreases as the radius increases. These McKibben air muscles act very similar to human muscle with respect to the forces they output over their change in length and forces acting on them.

There were several companies that produce commercial air muscles, such as Shadow Robot and Festo. The purpose for using air muscles to create a robotic arm was the intuition of the design itself. The final arms would potentially be used to perform tasks, such as micro vascular surgery. Instead of using a joystick to move implements on a robotic rod, which was often awkward or difficult. The operator of these designs would be using glove controls to move hands that worked exactly like those of the operator. This would decrease the burden on the operator performing complex surgery, for example.

The first team designed a human scale hand that used the air muscles to cause a hand to close its individual fingers. This was the first characterization of the air muscle for this family of projects. The second team designed a hand with all of the degrees of freedom of a human hand for the middle three fingers. They also continued with the characterization of the air muscle and improved upon designs of the air muscles they constructed. The third team created a robotic hand with five fingers and nearly all of the degrees of freedom of a human hand.

Designing an artificial limb using these muscles was not an easy task. A lot of work was involved in just machining parts and assembly, let alone all of the calculations and testing that needs to be done on both the mechanical and pneumatic systems. The previous iterations of the artificial limb project have all gone through the process of testing their designs after the prototype had been built. Each team ran into issues, such as the non-linearity of the McKibben air muscles, mechanical issues, or problems with controlling the limbs during testing which slowed the progress of the project.

This project's goal was to design and refine a simulation system that can be used to help design and test both the physical designs and the controls system. A controls system used to control a robotic arm can also be used with the computer simulation developed with a very small, non disruptive, addition. This high fidelity simulation should help future project iterations with the design process.

PROCESS

The Prototype

A physical prototype was made of the elbow to provide a comparison for the simulation as well as add to the solved designs for the human arm. The air muscles used were of the same materials as the last iteration, P09023, who spent a lot of time perfecting the designs.

A deviation from the last iterations' designs was the pneumatics. Previously, four 2-way, 2-positions single acting solenoids were used for each degree of freedom (DOF) from Roessel & Company Inc. They required one relay each. All of these solenoids attached to a non-standard manifold and required odd fittings. For this iteration, a single, 5-way, 3-position, double acting, center closed solenoid was used. Diagrams for each set up were shown in figures 1 and 2.

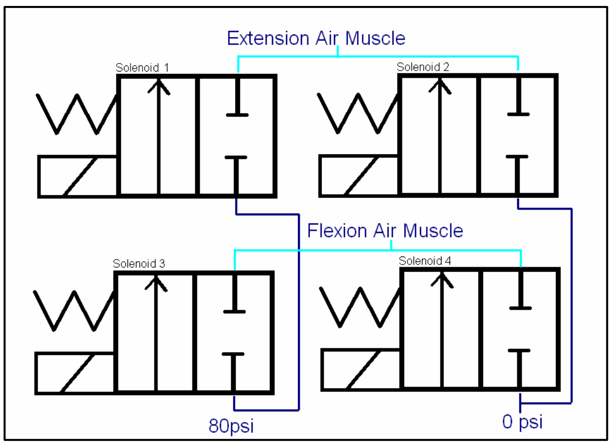

Figure 1 - Four 2-Position, 2-Way Solenoids for 1 DOF

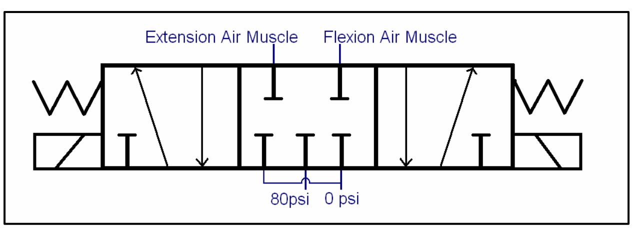

Figure 2 - 3-Position, 4-Way Solenoid for 1 DOF

Another adaptation from the previous team's work was cabling. The previous team noted that the forces acting on the cable could cause tearing and chaffing. This also decreased the energy transfer from the air muscles to the moving parts. More was taken into account for the design for the elbow in terms of cabling. For example, .35" pitch chain was wrapped around a 1.6" sprocket fixed to the forearm. The air muscles attached to the chain on either side of the sprocket. For the elbow, four air muscles were used (for increased power over a single air muscle in either direction). The air muscles' length was 13 inches when not pressurized. This gave about two and a half inches of displacement and four inches were needed to make the elbow complete the motion.

The air muscles were filled or voided with air through the solenoids. The solenoids were controlled by relays connected to a PC. NI's LabVIEW was used to control the relays and also controls the user interface.

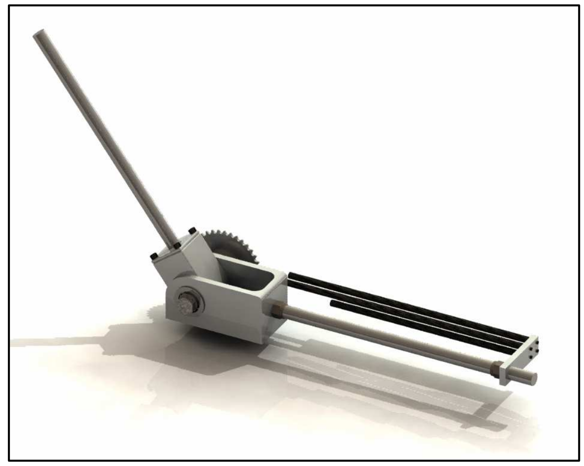

Figure 3 - SolidWorks Model

All of the CAD work was done in SolidWorks 2007. The elbow, shown by its self, is shown in Figure 3. SolidWorks 2007 was the program of choice because it was the only version of SolidWorks compatible with the simulation software package, called the Mechatronics Toolkit.

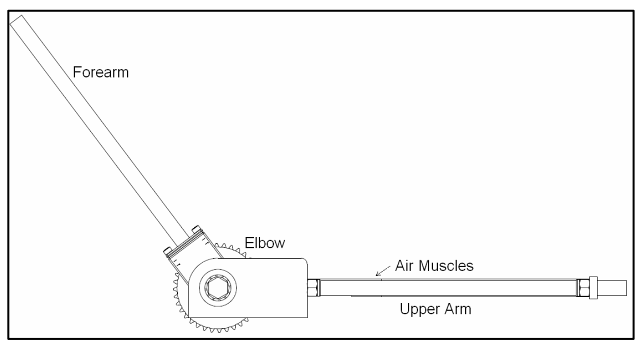

Figure 4 - Elbow Side View

The air muscles operate between a slight vacuum (~-5psi gage) and 80psi gage. Flow reducers were also placed in-line with the solenoid to decrease the speed with which the air muscles activated without reducing the pressure. The adjustable flow control valves allow for greater position control.

The Test Stand

The purpose for the test stand was simple; it had to hold the arm and sensors and accommodate its motion. To meet these needs, the specifications for it were developed. Firstly, the size of the arm was considered. The stand had to be large enough to hold the arm and sensors, and it had to be sturdy enough to withstand the arm's motion. Also, enough space was needed so that the arm can be secured to the stand and that any wiring or tubing required for running it could be present but out of the way of the arm's motion.

Many iterations of the stand were drawn out; all of them would hold the arm well enough, but none took into account the sensors or wiring. The final design fixed this problem. The stand consisted of a metal plate and a wooden base. The plate was slotted to hold U-bolts, which would clamp the arm down. These slots would also be used to connect the arm to electronic components. All of this was supported by the base, and separated by spacers, providing four inches of space to manipulate the wires and U-bolts. The base was twice the length of the plate; this allowed for mounting the sensors as well as clamping the stand to a table to provide the sturdiness required to remain motionless while the arm moves.

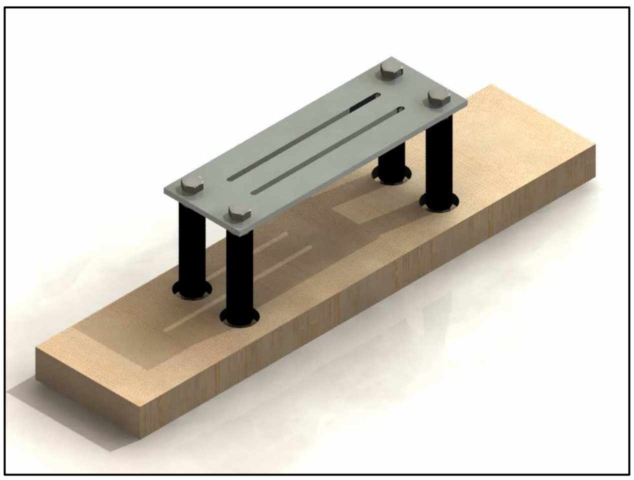

Figure 5 - Final Test Stand Design

Testing of the simulation and the prototype was implemented in two parts. First, the simulation model was moved to different positions and the measurements for actual position and forces were taken. After measurements were taken, the prototype was moved to the same positions and the same measurements taken. If the two sets of measurements were the same, then that signified that the simulation was working and accurate. If the measurements were not in sync, then action would be needed to explain and rectify the difference. Also, through testing the validity of the model in this way, testing of the control system was being done simultaneously. The controls were used to move the arm and the model, so if they both moved similarly and as expected, then the controls were sufficient in predicting the motion of both the simulation and the physical prototype.

The Simulation

The core of this project was the computer simulation. The simulation focuses on the kinematics of the model, especially the forces output by the air muscles.

Figure 6 shows the general system dynamics. The controls system controls both the computer model and the physical prototype. The computer model can be used to test future controls systems and predict the kinematics of a physical prototype. The physical prototype built by this team is meant to test the dual acting controls system and to be compared to the computer model to ensure accuracy.

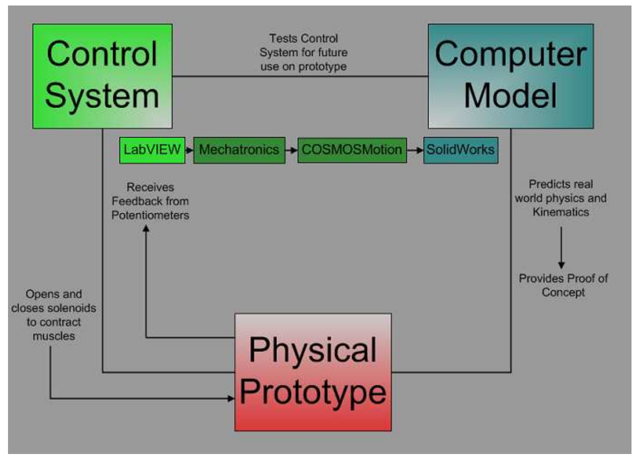

Figure 6 – System Flow

Figure 7 shows the general input flow from the user to both the physical prototype and the computer simulation.

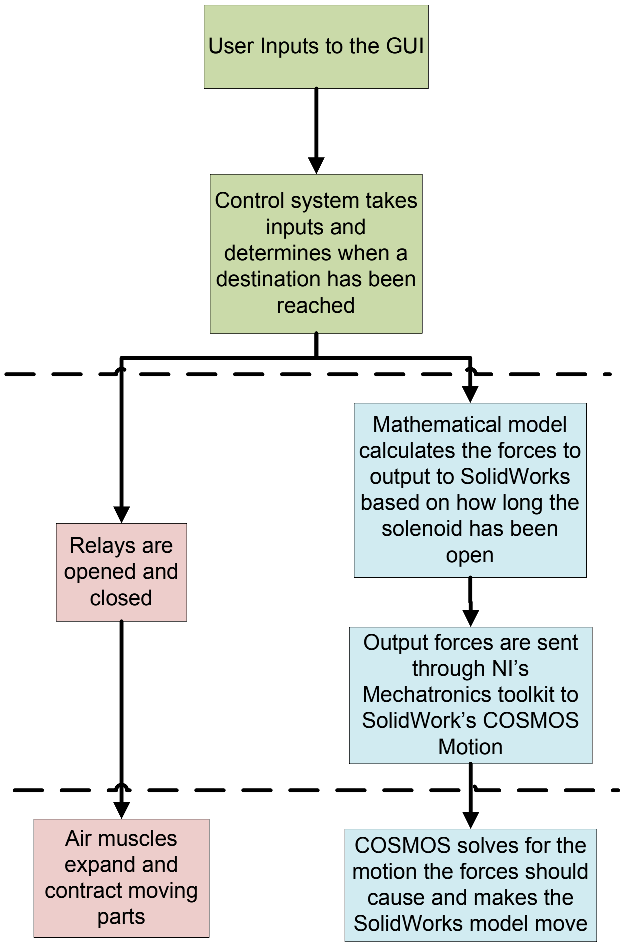

Figure 7 - System Flow

In addition to the physical prototype, a SolidWorks model was developed. The model reflected the desired physical parameters based on the engineering specifications.

In order to control both the physical prototype and software model, a control system was developed using LabVIEW. A general interface was used to output to both the prototype and model simultaneously. The accuracy of the software model could then be compared to the actual motion of the prototype.

Testing

Before the entire system could be used, the different components needed to be tested. First, the relays were given power to make sure they were working. The same test was done for the solenoid and vacuum pump. To test the software, the relays were set to turn on at 20 psi for 90 seconds.

Next, the air muscles were tested. Each muscle was filled with air and then rated on a scale of 0 to 5 on its quality.

The force measuring equipment was tested after the muscles. Because a suitable spring was not available which was suitable for the purpose of this project, an elastic cord was used. The displacement of the cord was measured against the force pulling it. A linear regression model estimated the spring constant of the cord, k.

Once the spring constant was known, the cord was tied to the strain gauge. The cord was pulled to set displacements and the voltage measured. This allowed the force to be calculated from the spring constant and the force-voltage relationship to be estimated. Both of these constants were calculated using a linear regression model.

The math model was tested by injecting air into the muscles at three different time intervals; 0.05, 0.125, and 0.25 seconds. Data was collected and the curve fitted to it.

RESULTS AND DISCUSSION

All components tested did work as planned. The vacuum pump did not work at first and had to be rewired. The spring constant for the elastic cord was estimated to be around 0.212 lbs/in, and the strain gauge constant was estimated at 2347 lbs/volt.

The data collected for pressure fit the derived curves very well. The equations are shown in Figure 8 and the graphs for the data and the fitted curve are shown in Figures 9 and 10.

Fill :

$$P_{muscle} = (P_0 - P_{Tank})e^{(\sigma)t} + P_{Tank}$$

Hold :

$$P_{muscle} = P_0 - .28\,t$$

Drain :

$$P_{muscle} = P_0 e^{(\sigma)t}$$

Figure 8 – Pressure Equations

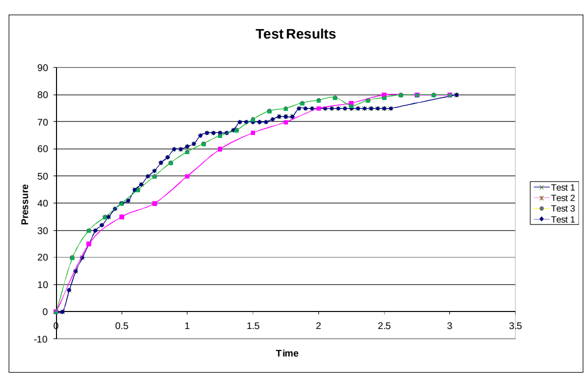

Figure 9 – Graph for Test Data

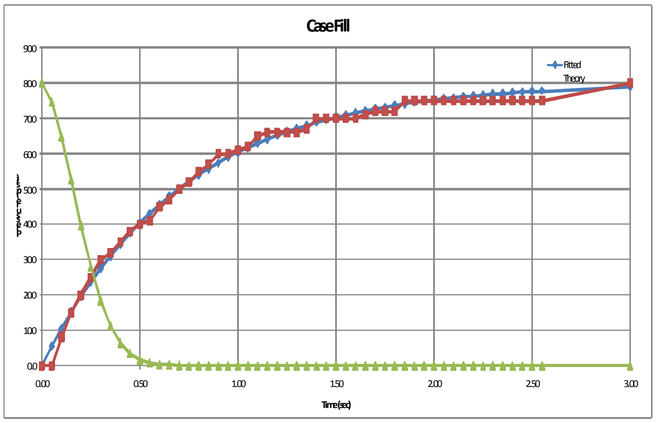

Figure 10 – Graph for Fitted Curve

The red dots are the collected data, and the blue dots represent the fitted curve. The calculated value for σ was approximately 1.43.

Overall, the mathematical model is fairly accurate. However, if it had been given more time, it could have been more refined. Also, the constants calculated along the way, such as the spring constant of the cord and the strain constant for the strain gauge, may come in handy in a future project, should similar methods be devised for testing and/or measuring.

RECOMMENDATIONS AND FUTURE WORK

The purpose of this project was to support future projects by easing the design phase for artificial limbs and testing for problems. Any future projects undergone on this track should benefit from the simulation and/or test stand.

There were several ways that future teams working on the biomedical track can streamline their design process. First and foremost, the projects involved with this track were meant to build off of each other. Subsequent teams should keep this in mind and try to not reinvent the wheel; the methods and results of previous work were available for that purpose. An example of this was the air muscle data. Muscles have been characterized fairly well already; unless there was a significant design change, the existing data works fine.

Most of the projects thus far have relied on similar types of parts and sources for materials for their prototypes. Future teams can use these same sources to develop their prototypes as well. Existing Bills of Materials could be very useful documents to review.

Overall, the projects which have been completed were thoroughly documented. Reviewing this material will be very beneficial and should nudge the progress of the track in the right direction.

Although much progress has been made since the inception of the artificial limb projects, there was still much that can be accomplished in the future. One of the most important was making the software universal. When the software can model more than just an arm, then teams will be able to use it for their own ambitions. The second most important task was reducing experimental error. As the limb was move over and over without some sort of homing algorithm, the error of movement will increase over time. Reducing this error would make a limb more accurate and human-like. Another topic of further study would be to add more joints to the repertoire, such as the shoulder or even the torsion of the torso. Eventually, these joints could be added to the ones which have already been developed to produce an entire working arm. Additionally, these more complex forms could be developed in the simulation software to predict their motions and detect any mechanical, pneumatic, or compatibility issues. In order to incorporate that, however, stronger air muscles would need to be developed. New muscles may also lead to the need and/or development for new and more efficient pneumatics systems. Also, methods for controlling the prototypes can be developed and enhanced, perhaps in time evolving into the use of the intuitive glove interface. One last thing to be considered was the scaling. If the future of these projects was to be in microsurgery or construction or hazardous materials handling, then different size limbs will be needed to accommodate these conditions.

ACKNOWLEDGMENTS

Casey, Arthur, and Andrew would like to give special thanks to Dr.Kathleen Lamkin-Kennard, Mr. Scott Kennard, Jim Breunig, Eva Ames, Tom Keane, Mr. David Hathaway, Dr. Mark Kempski, Mr. Rob Kraynik, Ryan Hellems, Dr. Steve Weinstein, Dr. Brown, Professor Palit, Bill Finch, Dr. Kozak, Dr. Varela, Eli Seidner (NI), Mr. John Wellin and Chappy.

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