

Team P09029

Project Summary

By

Casey Dill

Andrew Torkelson

Arthur Connors

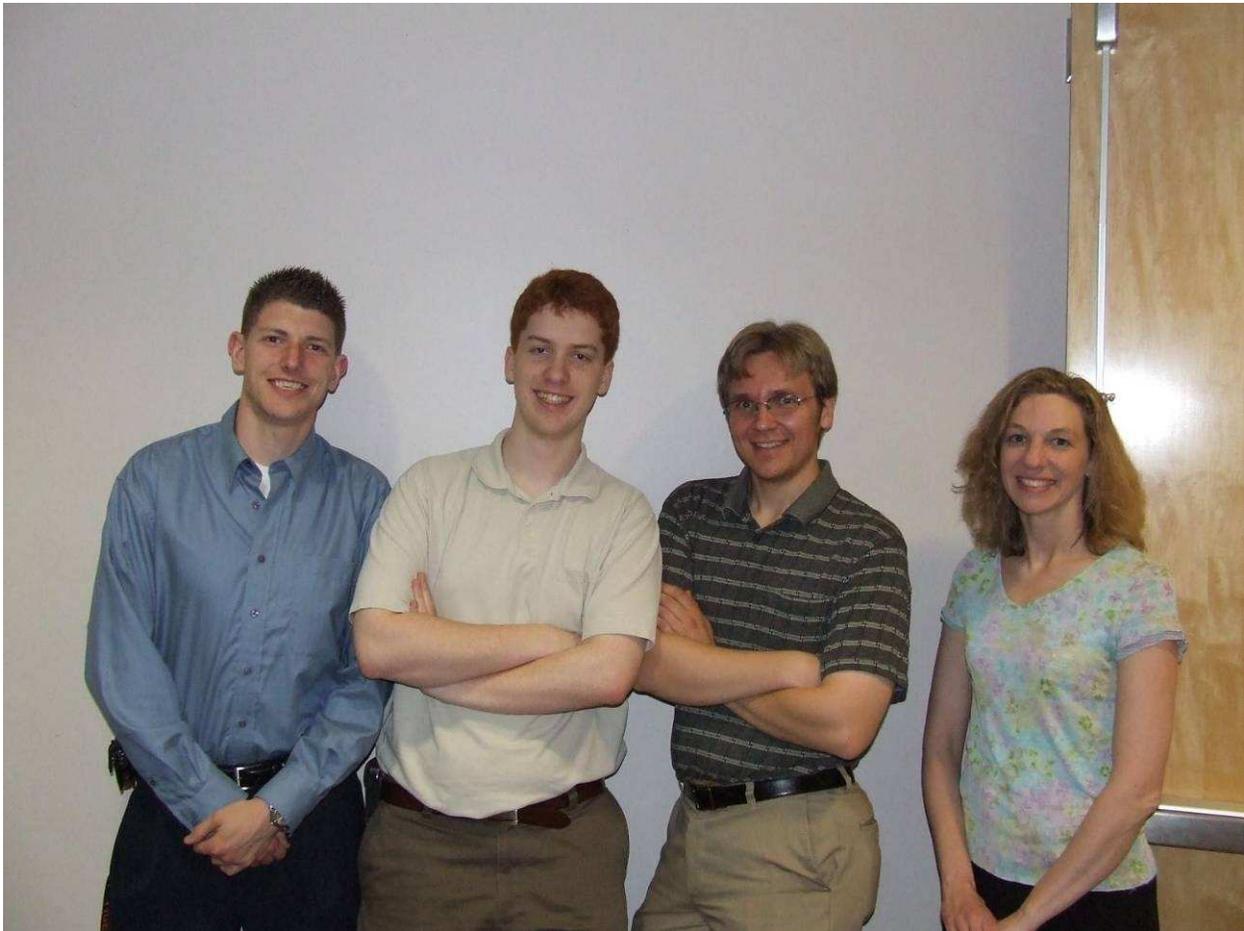
Dr. Lamkin-Kennard

ME, Team Lead

ISE

EE

Faculty Guide, Sponsor



Left to right: Arthur Connors, Casey Dill, Andrew Torkelson and Dr. Lamkin-Kennard

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Abstract

This project, the forth in a series of projects, set out to create a computer simulation for McKibben Air Muscles working on a robotic arm. LabVIEW was used for the graphic interface and mathematical modeling. The LabVIEW program controlled both relays to activate actual parts, and sent commands through a mechatronics toolkit which sent commands to Solid Works' COSMOS Motion, manipulating a 3D drawing of the physical part. Data was collected to adjust the mathematical model governing air pressure and output force, and the model improved. The final goal of a real time simulation working in parallel with the physical model was not completed, but the methods to create it were created.

Background

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.

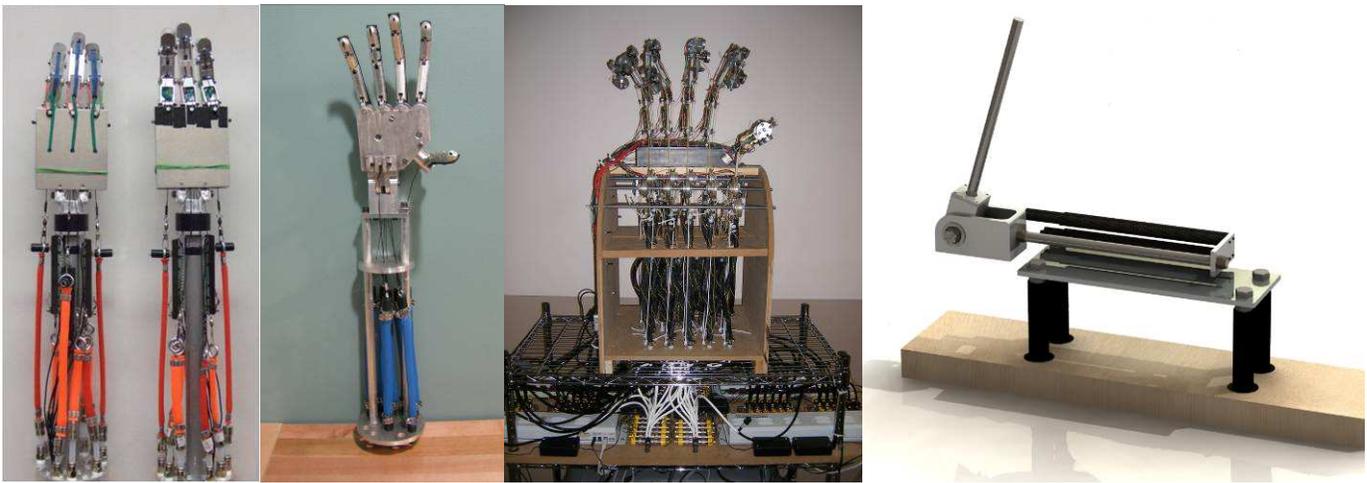


Figure 1 – Left to right: 1st generation, 2nd generation, 3rd generation and the 4th (current) generation

Project Goals

The customer needs were derived from the customer, Dr. Lamkin-Kennard through multiple interviews. Though the customer needs changed over time, the overall goal was the same. Dr. Lamkin-Kennard wanted a computer simulation that predicted what an air muscle would do to a physical model. The figure below shows the formal customer needs.

Revision #: 8		March 18, 2009	
Customer Need #	Importance	Description	
CN01	10	Must create a computer model that predicts the kinematics of an air-muscle controlled robotic arm. The kinematics of the wrist and elbow joints must be included in the model.	
CN02	9	The computer model created must predict forces that would be applied to the robotic arm design if air muscles were used as the force actuating mechanism.	
CN03	9	Must validate critical aspects of the design feasibility and the fidelity of the kinematic computer model using appropriate "breadboard level" physical prototype pieces (does NOT need to be complete physical prototype of arm). The breadboard pieces will also be used to develop the computer model.	
CN04	9	Must design wrist, forearm, and elbow mechanisms that have the same degrees of freedom as the human arm.	
CN05	8	Must develop controls software that can control both a computer model and a physical prototype. Control software must be capable of receiving displacement feedback from a virtual or physical model.	
CN06	8	Must complete an analysis of the forces generated by the air muscles to integrate with the computer model	
CN07	6	Motions must resemble human motions.	

Importance: Sample scale (1=lowest, 10=highest)

Figure 2 – Customer Needs

The Engineering Specifications were derived from the customer needs. The engineering specifications were split between the different pieces of the project for simplification. As the customer needs changed, the engineering specifications also changed.

Revision #: 13		May 20, 2009			
Eng. Spec. #	Source	Specification (description)	Unit of Measure	Marginal Value	Ideal Value
Simulation					
ES01	CN01	Computer model needs to be able to predict collisions	Boolean		TRUE
ES02	CN02	Computer model needs to be able to predict the forces acting on the arm components	Boolean		TRUE
ES03	CN03	Computer model needs to prove the design feasibility	Boolean		TRUE
Prototype					
ES04	CN07	Elbow has same number of degrees of freedom as the human hand	degrees of freedom		1
ES05	CN07	Bicep length	Inches	10-15	12
ES06	CN07	Forearm length	Inches	9-17	12
Test Stand					
ES07	CN03	Test stand needs to hold prototype stationary for testing	Boolean		TRUE
Movement					
ES08	CN07	Elbow Flexion resembles human motion (Elbow)	Degrees	130	150
ES09	CN07	Wrist Movement speed (median)	Degrees/Second	60	180
Controls					
ES10	CN05	Control system able to control both SolidWorks and Prototype	Boolean		TRUE
ES11	CN05	Control system able to take feedback from both SolidWorks and Prototype	Boolean		TRUE
ES12	CN06	Control system operates fast enough to control prototype (USB, Relay, DAQ, and Calculati	milliseconds	100-500	<100

Figure 3 – Engineering Specifications



Figure 4 – Left to right, a human arm, a mechanical arm and a simulated arm

Pneumatic Systems

The pneumatics system fills and deflates the air muscles controlling the motion. A solenoids valve controls whether air pressure is filling an air muscle, deflating an air muscle or holding the pressure.

There are two unique parts to this iteration's pneumatics design. First, flow control valves are used to stop the air muscles from filling and deflating to fast. Flow control valves don't change the steady state pressure, but they control how fast the air moves. Second, instead of using four relays to control four solenoids per degree of freedom, a single 3-position, 5-way solenoid is used, controlled by two relays. A stand-alone solenoid was used for this project because only a single degree of freedom was built. Future teams using more systems can take advantage of mounted solenoids, providing a built in manifold, requiring less connectors. Using this set up will take 75% less parts for the same motion as previous teams have used. A 5-way valve is used (connecting the two venting ports) instead of a 4-way valve, because the 5-way is more common, thus costs less.

For future teams, we would recommend brass fittings for the air muscle ends instead of nylon. Brass machines nicely, and is usually the material of choice for pneumatics. Because it is harder than nylon, it is also less likely to be the source of leaks. Having the team make them, instead of a lab assistant, is highly recommended.

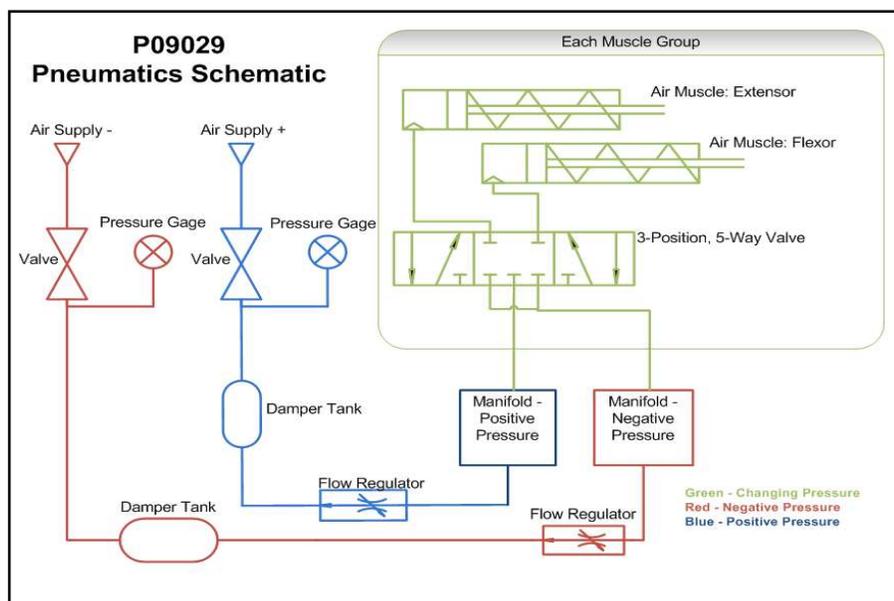


Figure 5 – P09029 Pneumatic Schematic

Physical Systems

The physical set up for this iteration involved an elbow joint on a test stand. The original design called for the forearm and wrist designs as well, so there are completed designs for these.

The forearm rotates about its axis representing the motion of the forearm. This feature was not utilized. The forearm also rotates around the elbow's axis, held by an aluminum block. This is attached to a bolt, acting as an axle, which in turn connected to a 1½" .35"pitch sprocket. Flattened edges of the bolt are used with set screws to maintain the connections. This means the as the sprocket rotates, so does the forearm. A chain is wrapped around the sprocket, and either end attached to air muscles that pull on the chain for either side. When one side pulls harder than another, the arm moves up and down. Two air muscles were used in either direction to get enough torque about the axis of motion. SolidWorks 2007 was used for all for all of the CAD work. There are four computers with SolidWorks in the CFD lab and at least two in Dr. Lamkin-Kennard's lab with SolidWorks on them. SolidWorks 2007 was used because the Mechatronics toolkit doesn't yet support newer versions.

For future teams we recommend keeping the cabling simple. Not using pulleys and small-radius bends greatly increases the usefulness of the air muscles. In our case, using a smaller sprocket at the elbow instead of a pulley system, made the motion work every time (instead of every other time failing/catching on something) and increased the force by almost double (because of the lack of additional friction).

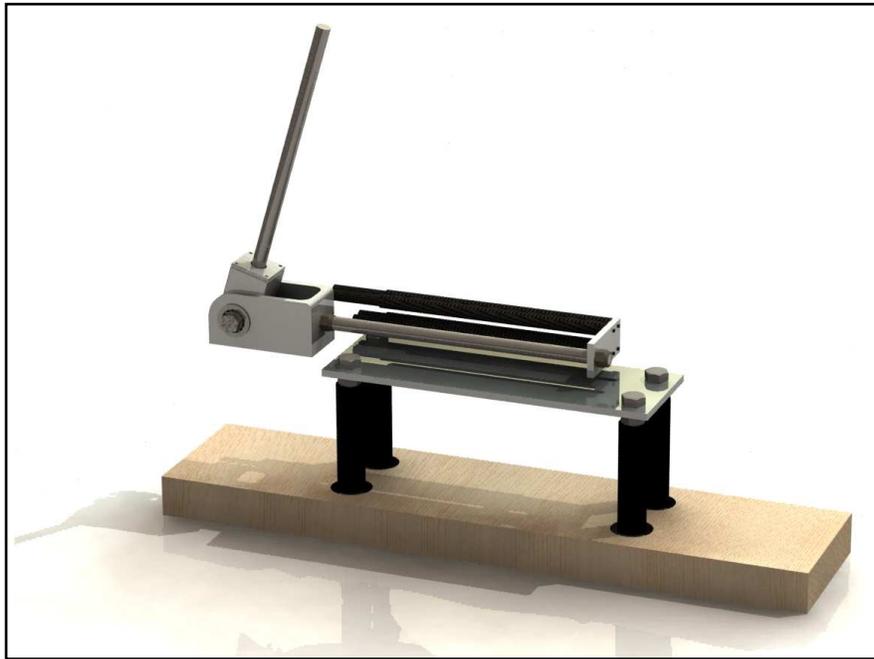


Figure 6 - CAD Model of the Final Arm on the Test Stand

Electrical Systems

The electrical system consisted of two subsystems. The primary subsystem involves the relay board and the solenoids. The relay board houses the solid-state relays that act as an open-circuit when they are not activated. Upon activation, the relays close the circuit and allow the 12V_{DC} from the DC power supply to trigger the solenoids. The second subsystem conditions the signal from the force sensor to a more measureable number. The force sensor is a strain gauge that varies resistance as force is applied to it. However, the voltage readings are rather minuscule and therefore the signal must be modified. In order to eliminate the noise margin the force sensor is inserted into a Wheatstone Bridge in an attempt to zero-out the differential voltage. To make the balancing process easier a bridge-balancing potentiometer is used. Upon zeroing-out the Wheatstone Bridge, the differential voltage is passed into a differential operational amplifier. The differential operational amplifier's gain is set by R_G, which is another potentiometer to allow for gain adjustment. The gain formula is noted as Equation 1. This signal is passed to the data acquisitioner (DAQ) [PMD-1208LS] for measurement in LabVIEW.

$$\text{Gain} = 1 + 50\text{k}\Omega / R_G \quad \text{Equation 1: Gain Equation}$$

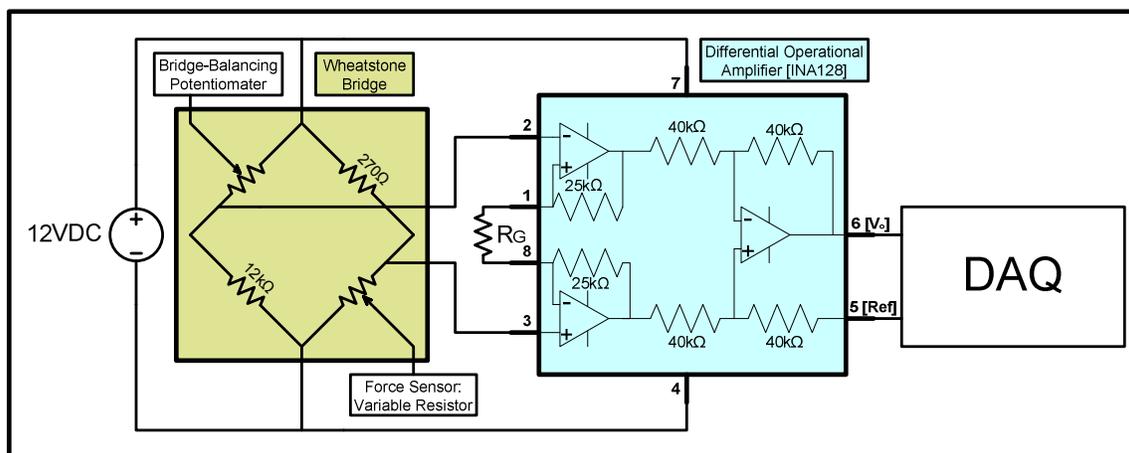


Figure 7 - Signal Conditioning Schematic

Programming

The two core programs for this project are LabVIEW and SolidWorks and a toolkit to form a communication link between them. These software packages are SolidWorks2007 Educational Edition with COSMOSMotion 2007 and LabVIEW 8.6. The toolkit is the National Instruments (NI) LabVIEW-SolidWorks Mechatronics Toolkit (Alpha Version 01). LabVIEW uses the Toolkit's functions to interface with SolidWorks through COSMOSMotion, a SolidWorks add-on. Some of these functions include initiate references, get part, set force, build force, simulate, delete simulation, delete all forces, and close all references. These are displayed with NI's descriptions in Figures 8-15, respectively.

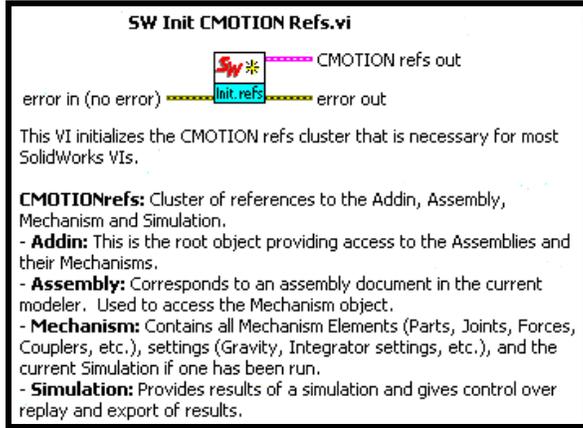


Figure 8 - Initiate References

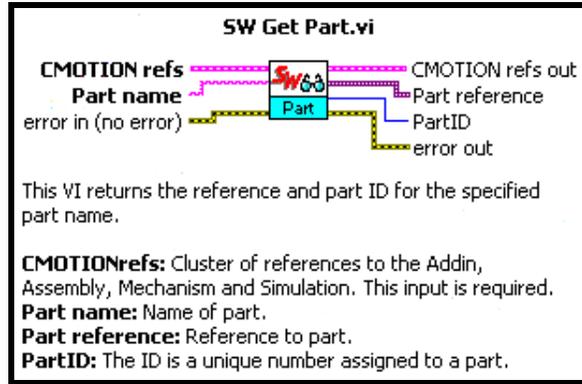


Figure 11 - Get Part

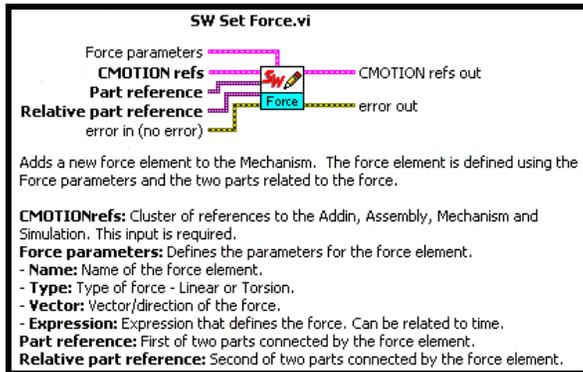


Figure 9- Set Force

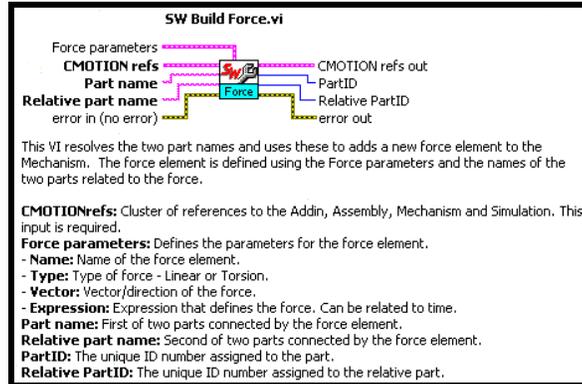


Figure 12 - Build Force

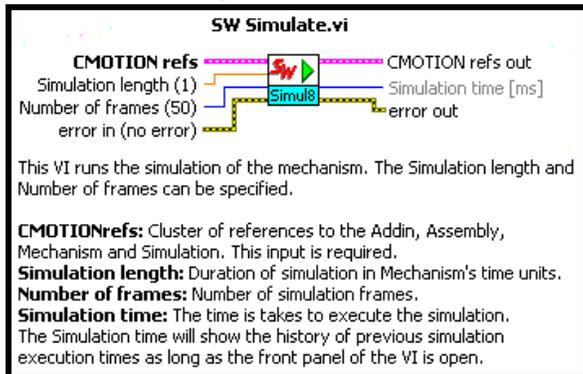


Figure 10 - Simulate

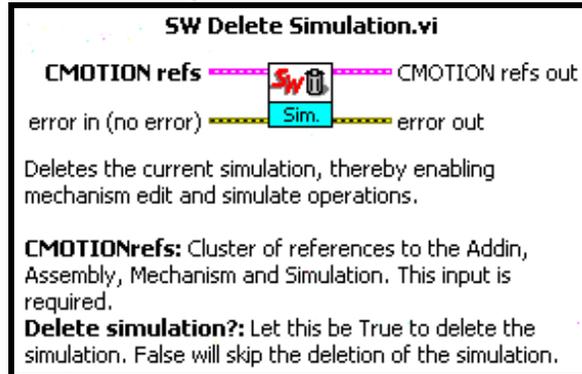


Figure 13 - Delete Simulation

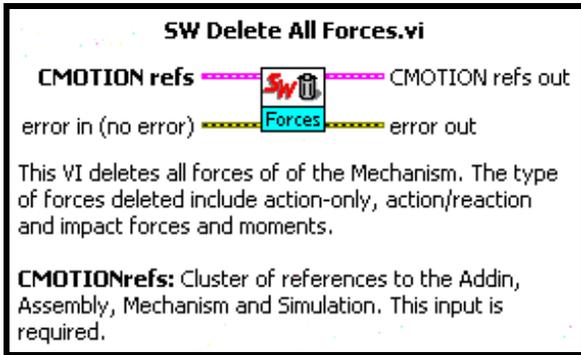


Figure 14 - Delete All Forces

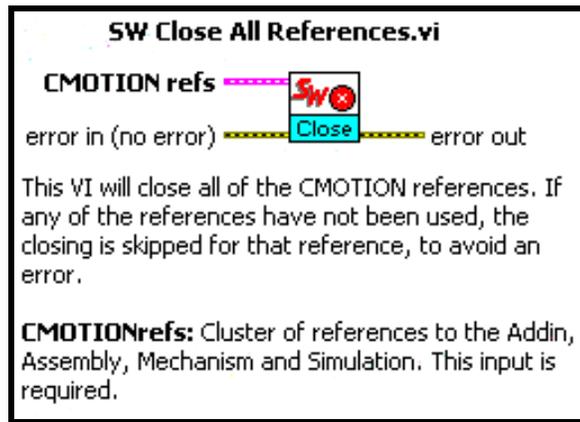


Figure 15 - Close All References

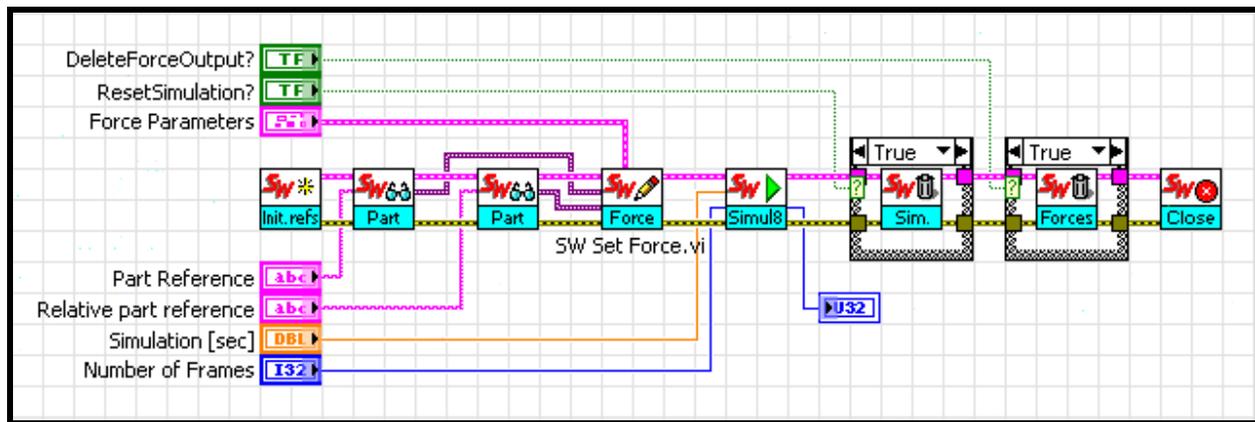


Figure 16 - Set Force Example

As can be seen in Figure 16, first the SolidWorks references are initialized, and then two parts are called as specified by the user. Then they are passed into the set force block along with the desired force parameters. The parameters allow for the naming of the force that is about to be simulated along with its type (linear or torsion), vector (x, y, z, -x, -y, or -z), and mathematical expression (in pounds-force). The developed force is then applied to the defined parts and is simulated in SolidWorks in real-time for the defined amount of time and with the defined number of frames. This example also includes the option to delete the simulation and the developed force. It is important to note that if the simulation is not deleted, a new simulation will not be able to run. This is because SolidWorks stores the simulation to be replayed in SolidWorks. Also, trying to run a simulation through LabVIEW when a simulation already exists does not generate an error despite the inability to run a new simulation. On a similar note, if the generated force is not also deleted it will be added to the newly generated force in the next simulation potentially causing undesired outcomes as forces accumulate. Lastly, SolidWorks closes the references used for the simulation.

Other conditions to be monitored in order to avoid potential simulation errors are:

- Excessive forces: Large forces can lead to overshoots of a part's given constraints, particularly distance limits. This occurs when COSMOS Motion's solver (COSMOS Motion->Options->Solver) has a step size that is too large to detect the collision in a given interval. Simply put, the part may pass through the collision plane before the solver has the opportunity to notice. Therefore, decreasing the step size or the force value will help avoid this overshooting condition.
- SolidWorks Assembly Crowded with Colored Shapes: To turn off the various colored shapes, hide the global symbol display (COSMOS Motion->Options->Display->Global symbol display:Hide)
- Displays Text Box at Runtime: To turn off solver messages (COSMOS Motion->Options->Solver ->Solver Messages:No Messages)

- Simulation Running Slow: There are various ways to try to reduce the amount of time it takes to simulate. Try reducing the duration, number of frames, accuracy, or solver time step or try increasing the fast increment under frame parameters (the number of frames to skip between each animation frame).

The hardware prototype system built in parallel was controlled to check and improve upon the mathematical model. Again, LabVIEW is being used as it is able to output to the relay board and also as it offers a user-friendly interface. In order to output to the Measurement Computing (MC) relay board [USB-SSR24] another set of developer-specified functions are required. Measurement Computing issues a CD with its products which contains universal libraries for Windows and for LabVIEW, an installation application called InstaCal, and various hardware manuals. It also offers the functions for communication between LabVIEW and the relay board and data acquisitioner. Figure 17 shows how the digital bit out function is used to interpret a Boolean array into specific outputs to be sent to the relay board. The Boolean array is developed based on the particular muscles to be activated for a given time.

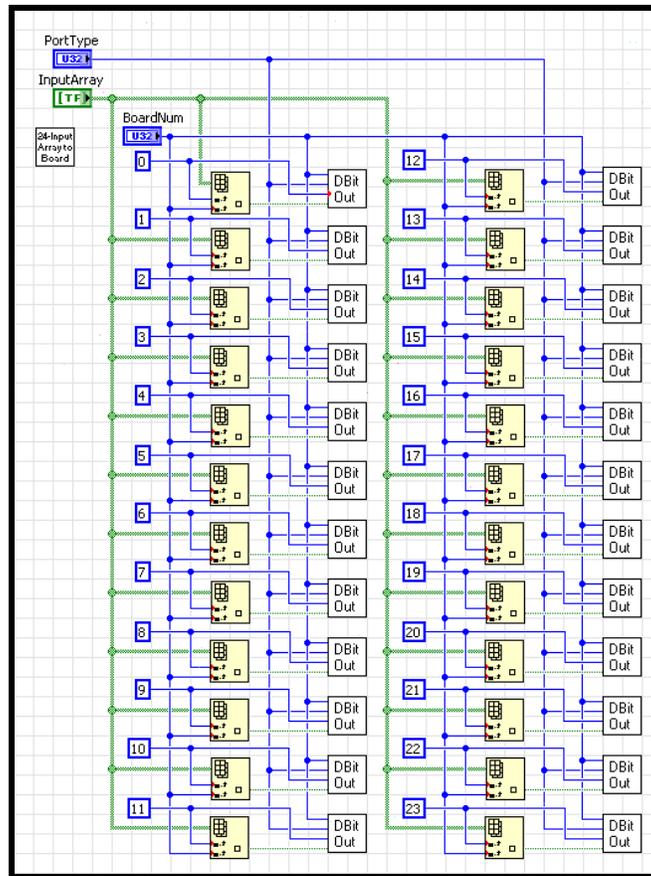


Figure 17 - Boolean Array Input to Relay Board Output

Then a DAQ takes readings from potentiometers to indicate how far a joint has translated or rotated. Feedback circumstances can then be considered. It is important to note that the resolution, or accuracy, of the measurements is directly correlated to the sampling rate. This is limited by the DAQ as well as the mode it is in (software-paced, continuous background/foreground or burst) and the number of channels being sampled simultaneously. To offset this situation, a flow restrictor can be placed in line with the air muscle(s) being used to reduce the rate of either filling or venting and therefore increase the overall resolution of the measurements being taken.

Results

To perform different tests on the elbow, a test stand had to be constructed. 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.

Once the stand was completed, a few preliminary tests had to be run. The first of these was components testing. Each component (solenoid, relays, vacuum, etc.) were powered on to see if they would run as expected. Next, the spring constant had to be found for the elastic cord being used. Forces were applied to different lengths of string and their deformation recorded. A linear regression analysis was performed on the data to estimate the constant. A similar test found the constant for the strain gauge. The cord was pulled a set amount (giving a known force) and the voltage difference recorded. Again, linear regression estimated the constant. The results for the tests for constants are shown in Figures 18 and 19.

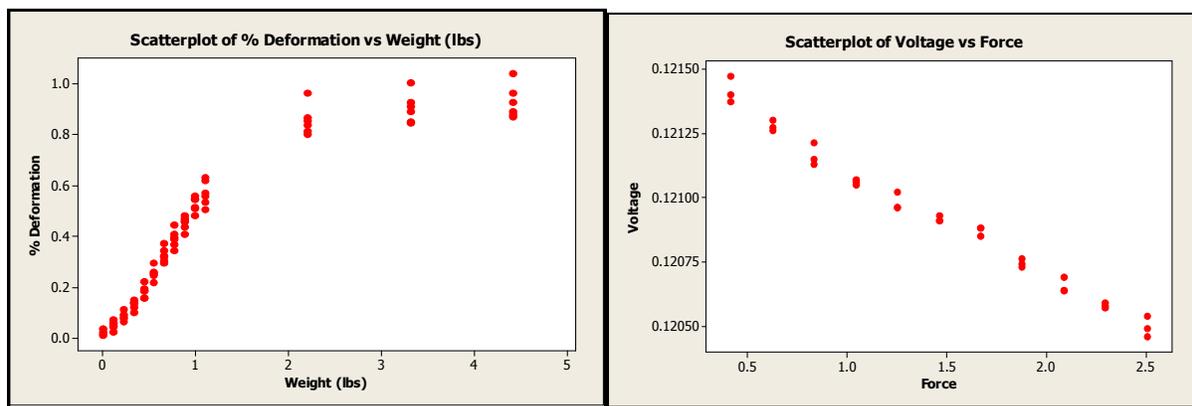


Figure 18 – Graphs of Spring Constant Data (left) and Strain Gauge Data (right)

$$k \cong .212$$

$$\text{Constant} \cong 2347$$

Figure 19 – k is 0.212 lbs/in, gauge constant is 2347 lbs/volt

The air muscles were tested to fit the math model. Air was injected into the muscles at three different time intervals (0.05, 0.125, and 0.25 seconds) and the muscles pressure was recorded. The data were plotted and the curve fitted to them. Figure 20 shows the data from the three tests plotted against each other. Figure 21 shows the curve fitted to the data. The blue curve is the theoretical function, and the red is the experimental data. The green curve is the function for emptying an air muscle.

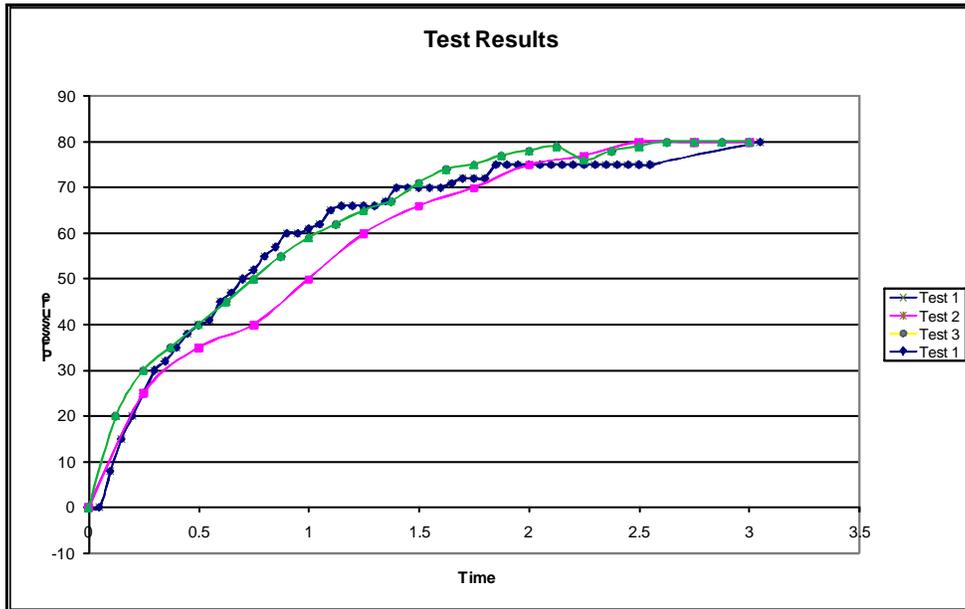


Figure 20 – Air Muscle Pressure Test Data

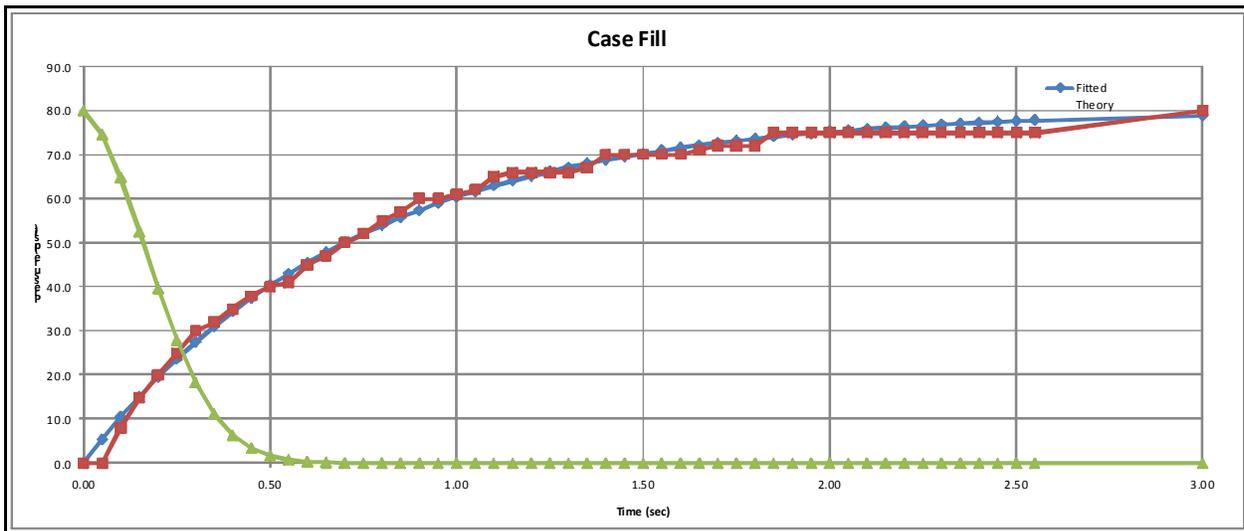


Figure 21 – Fitted Curve for Pressure Data

The data were also collected and plotted for position. For this test, the arm was set to the fully extended position by filling the “triceps” for two seconds at 80 psi, with the vacuum on. Two variations of the test were performed. In the first, the muscles were filled without homing. In the second the arm was homed between exertions by resetting it to the initial condition. Two iterations were done for each test, and the force at each time interval was calculated using the spring constant and the radius of the sprocket, around which the cord was tied. The results for this test are shown in Figures 22 and 23.

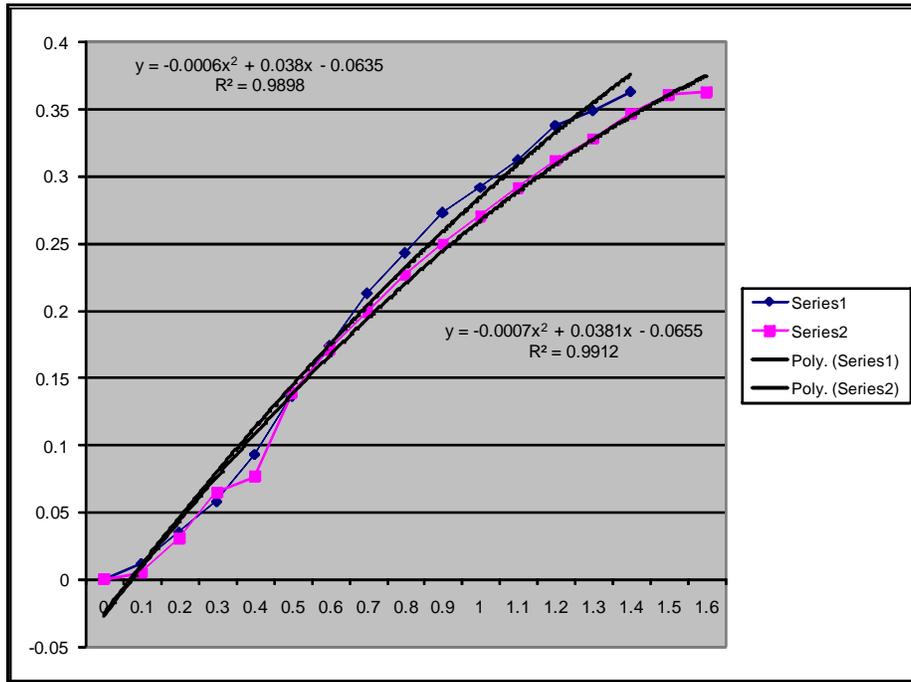


Figure 22 – Force vs. Time, derived from Position Testing, No Homing

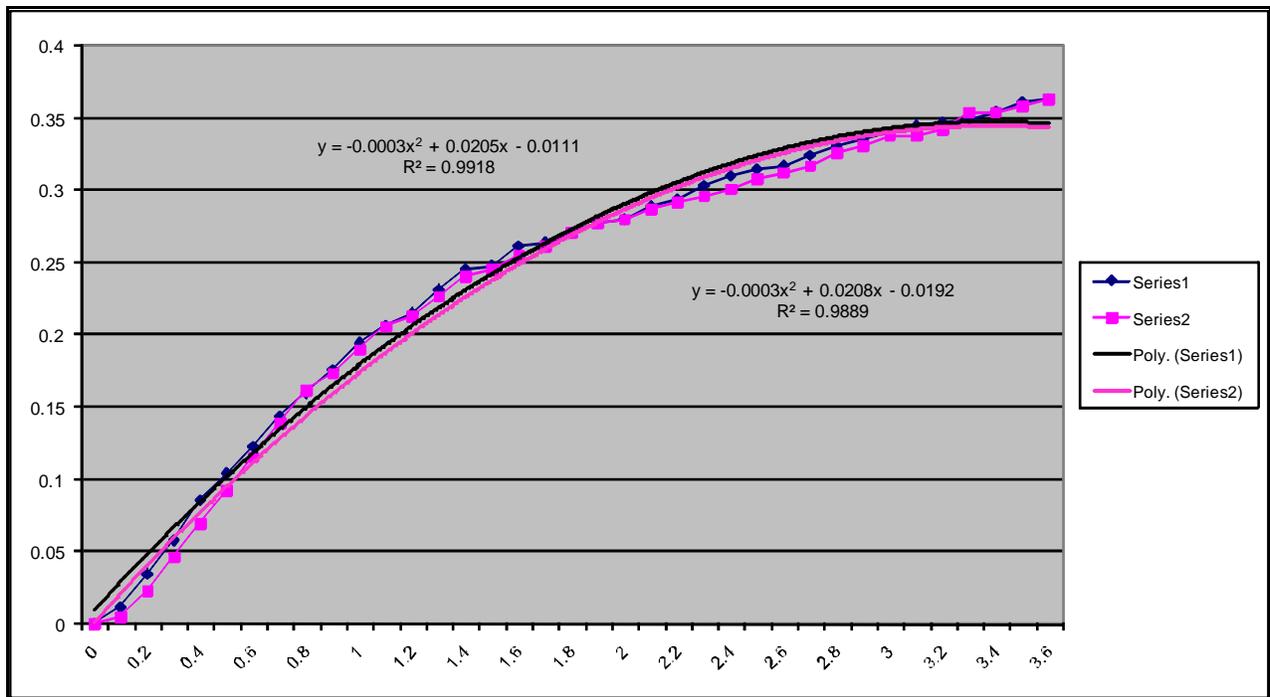


Figure 23 – Force vs. Time, derived from Position Testing, Homing Program results

For future teams, we recommend testing sooner, with larger sample sizes. Testing for this project started in the last week, so the accuracy testing outlined in the test plan was never carried out; instead, the tests discussed above were performed and analyzed. Plus, a larger sample always yields more meaningful results.

Lessons for the Future Generation

Local resources were one of the keys to getting everything done quickly. During this and previous projects good local resources were found. Local suppliers make for quick turnaround time (when a part is needed yesterday) and certain people in the area have been extremely useful.

For pneumatics, Roessel has been a great source. Mark Laitenberger was our contact there. He is familiar with the project.

For local parts, Cross Bros, Inc, is a good place to go. They have sprockets and chain on hand. Ordering a head of time from someone like McMaster Carr has a much better selection, but also cost more.

For help with pneumatic theory, Dr. Kozak (ME) is very helpful. For building real work pneumatic systems, Dr. Varela (ME) is very experienced.

For controls systems, Dr. Brown (EE) and Dr. Kempinski (ME) have also been helpful.

For coming up with designs, visiting the machine shop and talking with the guys there (Dave, Rob, etc) are the best. They can tell if a design is makeable, or if there is a better solution.

Pneumatic systems are the key to making the air muscle based arms work. This iteration we used a single 3-Position, 5-Way, closed center solenoid. This requires two relays and can control a single degree of freedom. Previous teams used four 2-way, 2-position solenoids, which took four relays, thus more controller board space. We also found no improvement using a vacuum to drain the air muscles. In fact, using flow control valves to reduce the flow of air into and out of the air muscles greatly helped. The flow control valves change the flow rate, but not pressure. This may be ideal for testing control systems, because the air muscles can be made to move very slowly, allowing more processing time to run control algorithms.

Another improvement for consideration is improving the end fittings on the air muscles. The nylon ends being used now have a lot of extra volume, which can cause problems when trying to make the air muscles fit into a small space. The nylon also is fairly soft. The threads can be easily stripped and bent, causing leaks. Brass is a choice material to use. It is very nice to machine and it is a common choice for pneumatic systems. For interfaces with the urethane tubing, however, we recommend the push to connect fittings. The barbed fittings can damage the tubing, they take up more space and are prone to leaking.

SolidWorks is great for CAD modeling, but it still has a ways to go for motion modeling with constraints. Keeping the constraints as simple as possible helps the system run the calculations faster and more accurately. It's as much an art as anything. Scott Kennard, Dr. Lamkin-Kennard's husband, is very helpful with this. He is familiar with this iteration of the project and may be able to help in the future.

Left over parts can be found in Dr. Lamkin-Kennard's lab. Using them to build prototypes early on would also be advantageous.