EE 449 Team 2, Pneu-MC Report

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I. INTRODUCTION

The goal of this project was to build a platform to test the fine-grained control feasibility of Gaylord-McKibben actuators. Gaylord-McKibben actuators are interesting because they are lightweight and inexpensive, and offer many potential applications in prosthetics, biomimicry research and human safe robotics.

After considering several options, we decided that a 3-degree of freedom robotic arm was a useful test case, providing an interesting control problem, with the ability to write legibly as an obvious proof of dexterity. The design and construction of such a system involved several major milestones:

First, several viable driver options for the actuators were investigated and prototyped. We attempted to construct a custom-built linear piston actuator to provide a very linear response for our actuators. In addition, we also investigated a traditional pneumatic system using off-the-shelf components. In practice, the piston driver was incapable of driving the actuators due to mechanical problems, so we decided to implement our project with pneumatic components.

Secondly, we performed a series of tests on the actuators in hope of finding a relatively simple model for actuator behavior. We found that the actuator displacement relative to input pressure was very consistent, with minimal hysteresis. In addition, we found there was a fairly linear region in the response between 1 and 3 bar of pressure.

Based on these test results, we designed a single actuated link prototype arm as a proof of concept. We were successfully able to implement reasonable control of the link angle using a PD based pneumatic control system.

Finally, we designed and implemented a 3 degree of freedom robot arm with an upgraded PID controller and computer control interface in attempts of reaching our control goals.

II. METHODS

Actuator Driver Selection

Two options were considered, built and tested to drive the actuation of the pneumatic muscles.

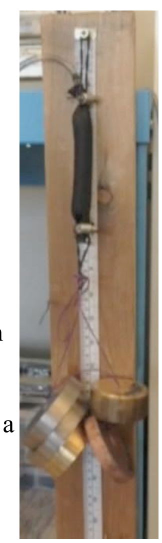
1. High Pressure Driver

The high-pressure driver is composed of two solenoid valves per actuator with a regulated air supply running at 4 bar. Each actuator had one intake valve to inflate it, and one exhaust valve for deflation. A Power N-Channel MOSFET connected to our control microcontroller drove each solenoid valve. This method provides a quick, powerful response using off-the-shelf components. We believed that the use of PWM to control flow rates would give us the desired control granularity we needed.

2. Hydraulic Piston Driver

This driver option consisted of a hydraulic piston attached to a driving servo using a rack and pinion mechanism. This method was theoretically more promising, as it could have provided more fine grained control response. However, our prototype was incapable of driving our actuators due to mechanical problems. Due to time constraints, we chose the high pressure driver option for our project.

Actuator Testing Setup



Testing was carried out with a pressure gauge and a measuring stick to establish a relationship between inflation pressure and displacement length. The pressure vs. displacement testing was carried out with different loads to observe the actuator's characteristics with varying loads. The tests resulted in a fairly linear region of displacement as a function of pressure for the region of 1 bar to 3 bar. There was about 3 cm of effective displacement in this region. The displacement of the muscles as a function of the force exerted by the loads showed that for a set pressure, the muscles wouldn't displace much with varying loads (.65 kg, 1.3 kg, 1.83 kg, 2.26 kg, & 2.27 kg). The characteristic curve for the actuators are shown in figures I and II.

Single Link Robot Arm

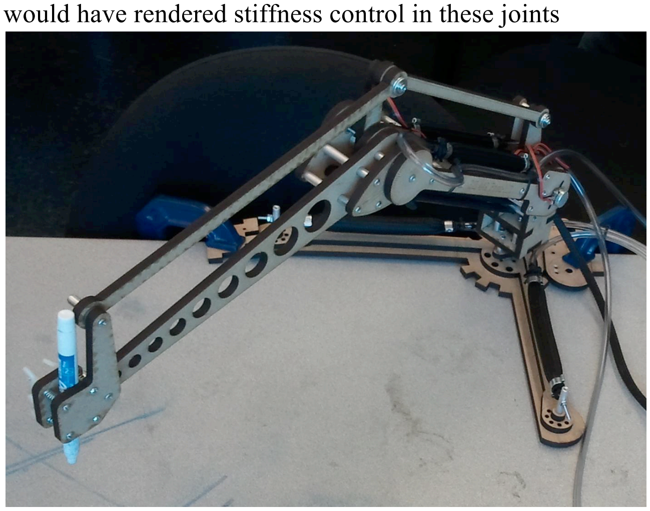
Our intermediate prototyping goal was to build a 1 Degree of Freedom (DoF) prototype as a proof of concept for the construction methods and control concepts planned for the 3 DoF arm. Custom components for the arm were designed using standard CAD software, and then laser-cut from ¼"

MDF. This allowed us to rapidly prototype and test components with minimal lead time.

Once rigged, the actuators proved quite impressive with a very fast response time and they were robust enough to move the arm even when under load. Based on our tests, several actuator construction improvements were proscribed to prevent binding and breakage of the actuator mounts, and to provide easier adjustment and calibration. The original actuators had large screw clamps that would bind and wear unevenly with the arm movement. In addition, the muscles were attached at both ends by small solid core wires, which could not handle the strains involved with repeated activation. In order to solve these problems, smaller pinch clamps were used in actuator construction, adjustable threaded mounts were used to rig the actuators on one the adjustable end of the actuator, and thicker, stranded wire loops were used for the other chassis anchor point.

3 Degree of Freedom Robot Arm

The 3 DoF robotic arm was constructed in similar manner to its single link counterpart, albeit with a significant change in scale. The final mechanism consisted of 6 actuators (2 per link), 12 solenoid valves (2 per actuator), and a newly added pressure sensor feedback circuit to measure the pressure in each actuator. To reduce weight at the end of the arm, all of the actuators for both links 2 and 3 were mounted on the second link, so as to be closer to the base. In practice, it was found that the arm was over-actuated, and that the final two links could be powered by 1 actuator each due to gravity. This improvement could have significantly reduced cost, but would have rendered stiffness control in these joints

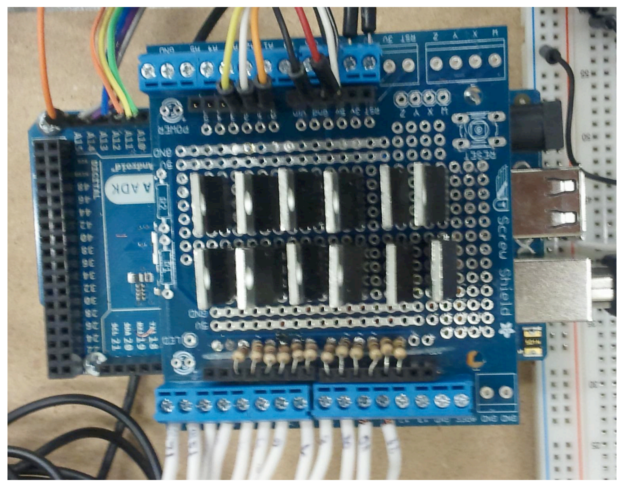


impossible.

Kinematic software for the 3 DoF arm was implemented in Python on a host PC, to leverage the increased floating-point capabilities of a PC, and then properly scaled joint angle values were transmitted to the arm controller over a serial link. In addition, this allowed for the implementation of a simple PC side GUI, to easily draw movement trajectories using a mouse. The GUI also allowed us to visually monitor the status of the control system, by rendering the arm's current position against its target location.

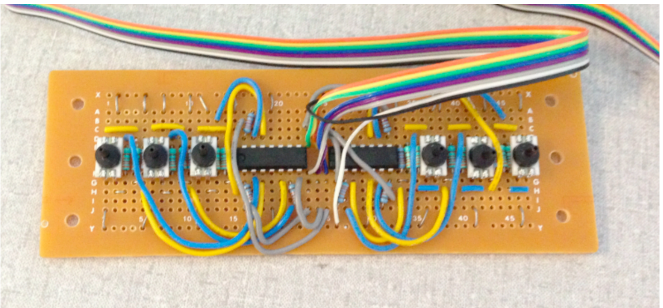
Solenoid Driver Circuit

The complete driver circuit for the 3 DoF arm consisted of 12 N-channel Power MOSFETs, each driving a 24V solenoid valve. The final circuit was built soldered on an Arduino screw shield mounted on top of our microcontroller. Due to weaknesses in our circuit assembly methods, this driver board was plagued by troubleshooting issues, and caused several delays to our project. The wiring was soldered beneath the shield within a very small area. This cramped wiring led to constant checks for shorts and continuity. In addition, several of the MOSFETs had to be replaced due to overheating and mechanical stress from repeated soldering. In the future, a custom built PCB with better buffer circuitry and heat management techniques would be highly beneficial to this project.



Pressure Sensor Circuit

The pressure sensor circuit consists of 6 gauge pressure sensors connected to the internal pressure of each of the 6 actuators. The desired benefit of the pressure sensor circuit long term was to allow for stiffness control to be implemented in addition to position control. Each pressure sensor is essentially a Wheatstone bridge with a differential voltage output proportional to the input pressure. This small voltage difference is fed into TI TLV2474 rail-to-rail op amp ICs to be properly scaled for our micro-controller's ADC circuit. The sensors provide nearly perfectly linear voltage response to input pressure. However, they varied from one other in the recorded voltage output for a given pressure. This variation was overcome using software calibration at atmospheric pressure. Due to time constraints, we were not able to fully incorporate pressure feedback into our control system. However the pressure sensors were used to provide precise physical actuator calibration by holding the actuator pressure to the middle of the linear region during calibration. More work can be done in the future to implement the pressure sensors as another input to the control system for improved control system performance and stiffness control.



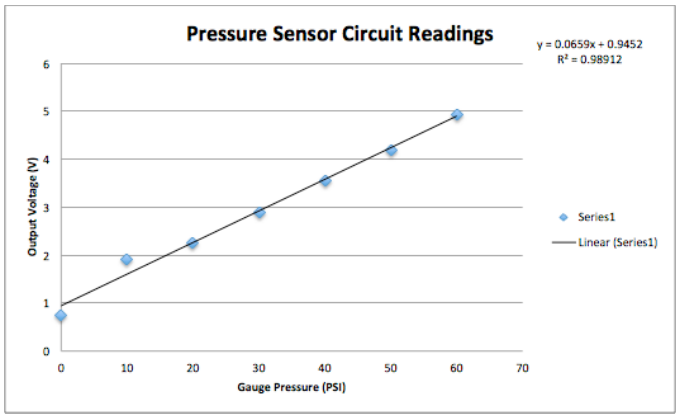


Figure I: Output Voltage of Pressure Sensor Circuit

Control System Implementation

Our control system was implemented using an Arduino Mega 2560 micro-controller, with custom-built daughter boards to drive our output solenoids and handle pressure gauge feedback. Position control for the actuated links was provided by PID control using feedback potentiometers. Our PID controller used a switching accumulator term to allow for quick response (PD control) while still leveraging the steady state error cancelling properties of an integrator term for small errors. Tuning of the PID constants was performed manually and was adjusted separately for each link, to account for the different inertia tensors of each link. Better actuator modeling and robot dynamics analysis could allow for simulation and fine tuning of PID parameters in the future, but that was beyond the scope of the time allotted for this project.

III. DISCUSSION

When testing our McKibben actuators, we found that the actuators have a near-linear operating region for displacement relative to pressure of about for air pressures between 1 kg/cm^2 and 3 kg/cm^2. Our joint position systems were designed with this region in mind. Testing of the actuators was carried out using a 1.5kg mass, however it was also found that varying the load had very little effect on their displacement characteristics. When pressurized, the actuators themselves exhibit spring-like behavior under load. Additional testing could provide a nice linear spring model for these actuators, allowing for stiffness control implementation, and better modeling of the dynamic response of individual actuators. Although the springs can be modeled as linear with respect to displacement, it was found from testing that they do exhibit variable K values, which is dependent on their current pressurization. An exact fit of the K values with respect to pressure was not found although it was observed that the K values for the actuators increased with pressure.

In our robotic arm design, each actuator was attached such that it could fully rotate a joint through a 90° range and remain in its linear region of operation. Once the 3 DoF arm was fully constructed control of each independent joint was achieved with an accuracy of +/- 5 °. However, the limited PWM resolution of the pneumatic valves used did not allow for the fine grained control necessary to reach our goal of +/- 1°. Thus our position control was not fine enough to write legibly with our given drivers. In addition, our arm design was built with mechanical simplicity as the first priority, but with poorly-thought out kinematics. Thus, some kinematic inelegance of our design added to our difficulties, providing an oddly shaped workspace for the task, and poor angular resolution in the workspace. Additional hardware revisions and additional PID tuning could partially solve these issues and render better accuracy. However, we believe that proper fine-grained control would require a better actuator driver solution.

IV. RESULTS

Shown below are the testing results of the McKibben actuator. Figure XX shows the characteristics of the actuators for the pressure range of 0 - 8 Bar. The actuator minimum activation pressure is seen to be approximately 0.5 Bar, while a linear region for displacement is seen in the region between 1 to 3 Bar. The pressure vs. displacement characteristics curve is shown with different load conditions. With the load approximately quadrupled it is seen that the change in behavior of the McKibben actuator is minimal, while the linear region is only slightly depleted.

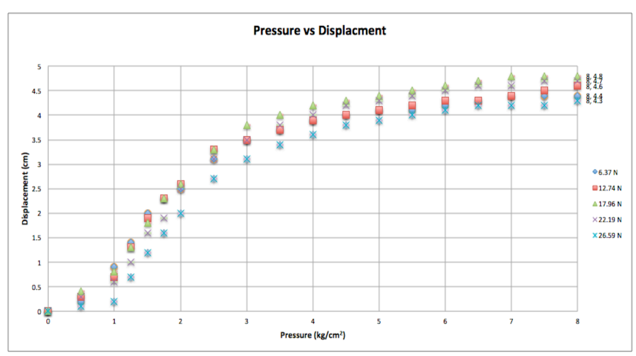


Figure II: McKibben Pressure vs Displacement Characteristic Plot

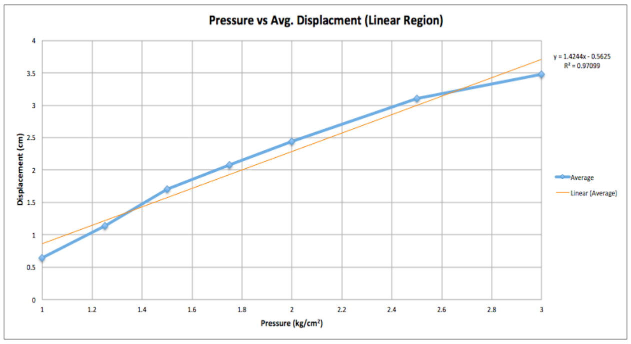


Figure III: McKibben Pressure vs Displacement

Control System Results

Unfortunately, the control system solution we developed proved incapable of reaching the desired control accuracy desired. When attempting to actuate our pneumatic valves with PWM, we found that the minimum pulse width required to open the mechanical valves was 15 ms. However, this pulse width often resulted in more than 10° of change in the affected links, leading to unstable control responses for small errors. This rendered our target application of writing impossible. With all attempts to that end resulting in garbled scribbles.

I. Conclusion

Although the desired position accuracy of +- 1% was not achieved, the McKibben actuators proved to be very powerful, and inexpensive method of articulating our robotic arm. Unfortunately, the driver options we chose proved inadequate to provide the control resolution we desired, but future work and improvements could realize our goals.

Potential for Future Work

Given the results we achieved, we still believe that these actuators have lots of potential, and could meet our control goals given more time and development. Additional modeling and more time tuning PID parameters could provide better control accuracy. In addition, more time can be invested into solving the mechanical causes of our control resolution woes. For example, we could examine using flow restrictors, proportional valves, or higher frequency valves to provide more resolution in our drivers. In addition, additional mechanical redesign of the 3 DoF arm could reduce slop and improve the angular resolution of our arm through better kinematics.

One promising direction of study would be to re-investigate our hydraulic driver option. Better mechanical design of these actuators, possibly using custom-fabricated piston components and drive hardware could produce a driver capable of powering our actuators, while offering extremely fine-grained control resolution, and a direct correlation between actuator force and driver current.

Once our control resolution goals have been met, the next logical step would be to spend additional time and effort modeling the spring-like behavior of the actuators. This could be used to implement link stiffness control in addition to position control. A good proof-concept task for this would be the ability to use a calligraphy brush in place of a pen. Hand in hand with this development would be to implement better incorporation of pressure feedback into our control system, resulting in a proper MIMO control solution. Additionally, adding strain gauges on the end effector could be used to implement adaptive control systems and hybrid control methods for our stiffness control system.

Another beneficial avenue of study would be to incorporate additional standard robot dynamics calculations and control improvements to improve our control system tuning for each individual joint. Jacobian analysis, velocity control and better trajectory generation could further enhance the performance of our arm for the stated task of handwriting and calligraphy.

Acknowledgment

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We would like to extend special recognition to the fall detection team for the hours of amusement we enjoyed watching them test their device.
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