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VARIABLE POSITION AND FORCE CONTROL OF A PNEUMATICALLY ACTUATED KNEE JOINT

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ABSTRACT

Pneumatically powered prostheses have the ability to restore function and improve the quality of life by providing external power, thus decreasing human effort. However, such prostheses are expensive because they use high performance servo valves and complex control systems. To overcome this limitation, a pneumatic actuator is retrofitted with cheap solenoid valves and controlled by pulse width modulation for continuous control. High fidelity control is achieved by using a negative displacement configuration in which pressure is released on one side to create motion. The performance of the system is demonstrated using a series of position, force control experiments and ability to withstand external impulses. The pneumatic system is cheap, has high repeatability, and accuracy. The main limitation is that the speed of response is much slower than a positive displacement system but better design of the solenoid valve and use of predictive control has the potential to alleviate this issue.

1. INTRODUCTION

For above the knee (transfemoral) amputees, a powered prosthetic device will decrease the energy expenditure associated with movement [1, 2]. The current, prevailing means of energy conveyance on prostheses are electromechanical, hydraulic, pneumatic, or a combination of two of the listed methods. Electromechanical systems, while capable of high actuation speeds and a readily available means to store energy in the form of electrochemical batteries, tend to possess a lower energy density than their hydraulic equivalents. Hydraulic systems, conversely, offer high power output for their relative size, but are severely restricted by the lack of a compact means of energy storage that does not require the inclusion of a hydraulic power unit [3, 4]. Pneumatic systems, while possessing a mid-range power density, high ease of energy storage, and inherently light weight medium, have the unique complexity of requiring a controller capable of compensating for the compressible nature of the medium.

Pneumatic systems can act to supplant electromechanical and hydraulic systems in leg prostheses and can serve as a viable means of actuation for such prosthesis as proposed by Wu, Zheng and Shen [5]. Pneumatic artificial muscles (PAM) have been utilized in place of traditional linear pneumatic actuators and are well known for their light weight, compliance and ability to simulate actual muscles [6]. The implementation of pneumatic control necessitates the use of a variable flow control system to facilitate intermediate movement between leg extremes. Traditional systems utilize a variable, servo actuated control valves to vary the flow rate of air in proportion to an applied electrical signal. They are both complicated and expensive, significantly increasing the cost of any prosthesis based on their use.

The main novelty of this work is the use of solenoid valves in place of pneumatic servo valves for high fidelity position and force control of the knee joint. Continuous control of the solenoid valve is achieved by using pulse width modulation. A unique feature of our pneumatic system is the use of negative displacement configuration in which the pressure is released on one side to create movement. This allows the use of higher pressures hence lower compressibility and better controllability of the actuator.

Nomenclature

Plot Nomenclature:

Units are as specified on individual plots for each data set. Designation colors are not consistent throughout the individual plots. Datasets identified as possessing the unit of “Var” have been recorded in values native to the Arduino microcontroller. “Var” units have a range of 0 to 1024 for an input and 0 to 255 for an output.

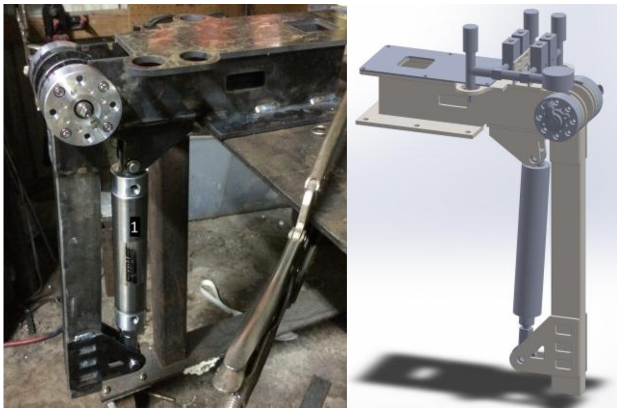
Equation Variables:

A_{in}	Targeted amplitude (deg)
A_{exp}	Experimentally obtained amplitude (deg)
E	PID error value
K_p	PID controller proportional constant
K_i	PID controller integration constant
K_d	PID controller derivative constant
t_{in}	Time (ms), measured from program start
t_{exp}	Time(ms), measured from program start
Θ_{target}	Targeted angle or pressure, depending on the instance of the PID control scheme.
$\Theta_{current}$	Current leg angle or pressure, depending on the instance of the PID control scheme.

2. METHODS

Hardware Configuration

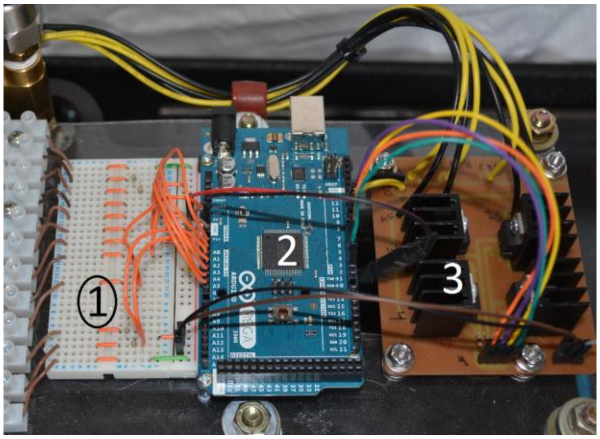
The experiment apparatus centers on an Arduino Mega 2560 microcontroller, which is utilized for general computation, feedback analysis, and data collection. The physical apparatus consists of a pneumatic cylinder (Grainger #6CZZ8) attached to a customized steel framework. Completely designed in SolidWorks, the framework is oriented and sized so as to approximate the motions of a rudimentary human knee joint. Emphasis is not placed on mimicking the physiological kinematics of the knee joint for this project. All rotational motion is isolated from the base through the use of dual sealed bearings to reduce the effects of friction on the experiment.



1 - Pneumatic Cylinder

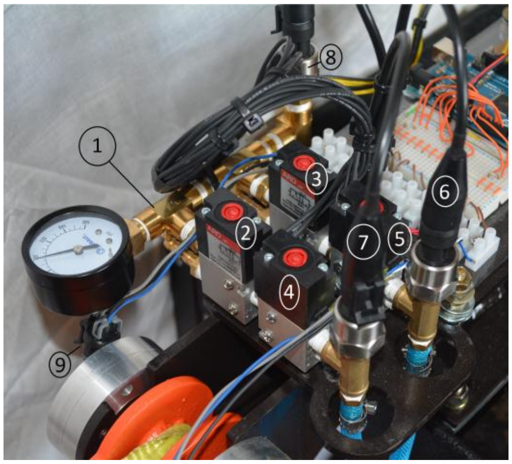
Figure 1: (Leg) Apparatus Framework, SolidWorks Model

Control of the pneumatic cylinder is achieved through the use of four ARO 2-position solenoid valves (#P251SS-012-D), oriented in a parallel series configuration so as to allow two valves for each port on the pneumatic cylinder. The valves connected to the air supply line act to direct the flow, so as to either intake or exhaust, while the secondary valves function solely to control the rate of flow through the use of pulse width modulation. As the valves each require approximately 0.3 amperes to fully actuate, they are electrically linked to the Arduino Mega 2560 via four TIP-31C based power amplifiers, Figure 2.



1 – Sensor Connections & Resistive Voltage Divider,
2 – Arduino Mega 2560,
3 – Solenoid Control Power Amplifier

Figure 2: Electronic Control Assembly



1 - Supply Line, 2 – “A” Directional Valve,
3 – “B” Directional Valve, 4 – “A” State Valve,
5 – “B” State Valve, 6 – “B” Pressure Transducer,
7 – “A” Pres. Transducer, 8 - Supply Pressure Transducer,
9 - Angular Position Sensor

Figure 3: Pneumatic Control Assembly

The sensor pack consists of three 150PSI #D4 pressure transducers and two MasterPro EC3048 throttle position sensors (TPS). The EC3048 TPS sensors are resistive in nature, functioning in an identical fashion to a standard potentiometer.

The air supply line is charged by a portable, 5 gallon, 150PSI air compressor, regulated to 100PSI for all experiments except the last constant force trial, in which the operating pressure is increased to 125PSI to compensate for the increased weight applied to the testing apparatus.

Data acquisition is accomplished through the use of the Parallax PLX-DAQ software suite, which facilitates the importation of up to twenty four channels of data directly into a Microsoft Excel spreadsheet. Data communication is accomplished via the onboard Arduino serial port interface operating at 128 kilobits per second.

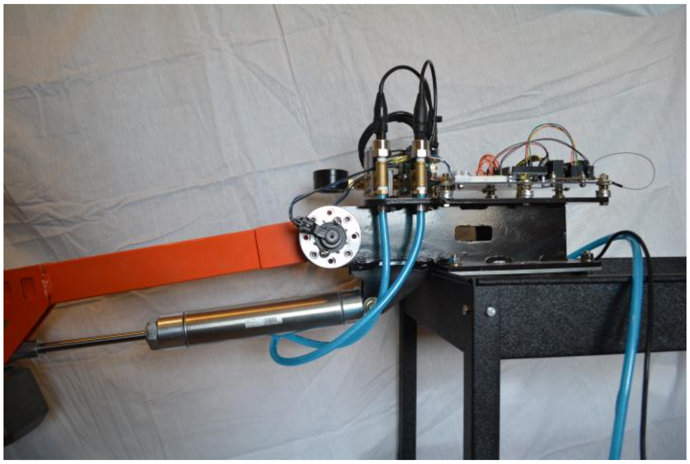


Figure 4: Completed Hardware Configuration

Pneumatic Configuration

All of the processes described in this report operate in a negative displacement configuration, or a configuration in which the medium is released from one side of the completely pressurized pneumatic cylinder to induce motion. Early attempts were made to operate in a positive displacement configuration, or a configuration in which medium is injected into one side of the ambient pressure cylinder to cause motion; However, it was quickly noted that at lower pressures the compressibility of the medium becomes much more pronounced and difficult to control. Almost no level of variable flow could actuate the un-loaded leg to a specific level without excessive overshoot and destructive oscillation.

Software Configuration

The software configuration is centered on a relatively simple primary command loop: check value and if the current value deviates from the target value, actuate the solenoid valves in accordance with the specified controller. The setup sequence contains the requisite input/output (I/O) calls and commands to reset the clock frequency on register 2 (digital I/O pins 9 & 10, Solenoid State valves) to 30 hertz, the optimal pulse width modulation (PWM) frequency for a standard pneumatic solenoid valve [7].

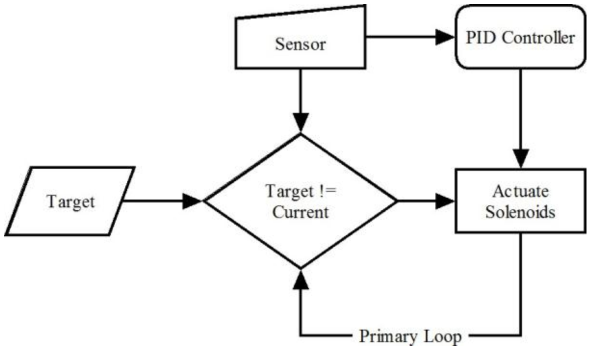


Figure 5: Primary Control Theory

As the equipped pressure sensors output a single, proportional voltage, the pressure update subroutine does not average values across the individual inputs. It does, in response to noise induced during PWM movement, average the values for each pressure sensor input over a number of individual readings, so as to smooth noise.

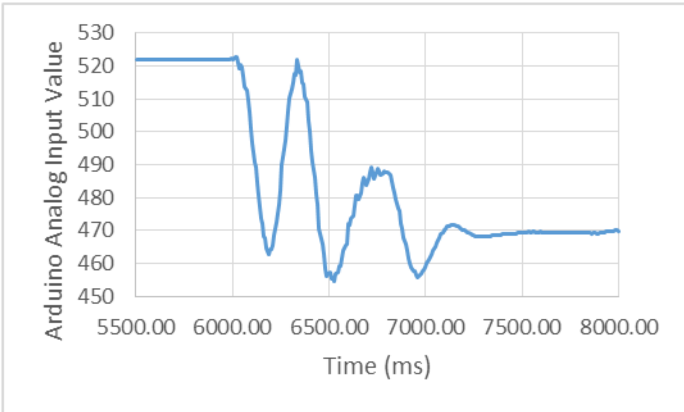


Figure 6: Pressure Variations due to PWM during Movement, After Smoothing Operation.

Control configuration:

Position control: The angular location and pressure control scheme controllers function similar to a standard proportional-integral-derivative controller (PID). The error value, the difference between the current value and target value, is calculated (Eq. I). This value is then utilized to calculate the output value using (Eq. II). Both PID control schemes were manually tuned to minimize overshoot at the expense of settling time. More aggressive control schemes utilizing higher gains may be utilized to decrease settling time but can run into stability issues when used on prosthesis.

PID Error

$$E = \theta_{target} - \theta_{current} \quad \text{(I)}$$

PID constant

$$PID = K_p E + K_i \int_{t_0}^{t} \tau dt + K_d \frac{dE}{dt} \qquad \text{(II)}$$

A scale constant is applied to bring the resultant PID value into congruency with the requirements for the solenoid control subroutine. The resultant value directly controls the actions of the solenoids throughout the program. To avoid premature solenoid failure, a dead band or space about the target variable in which all PID function ceases, is utilized. For angular positioning, this dead band takes the form of a two degree tolerance about the target angle, while for pressure regulation, the dead band takes the form of a one half unit tolerance about the target pressure.

In both the angular positioning and pressure regulation subroutines, it is necessary to institute limits to prevent the over accumulation of the integral component of the PID controllers. To accomplish this, commands are issued when the leg enters the dead band and enters a state of zero motion that cause the integral total to reset to a zero value, effectively causing the controllers to treat each move from the previous target as if it were the first move to have been made. While both subroutines contain the structure to be classified as PID controllers, the angular positioning and pressure regulation controllers utilize a derivative constant of zero. In addition, the pressure regulation controller has an experimentally determined integral constant of zero, due to the way in which the integral term tended to conflict with the long term operation of the subroutine. These values effectively limit the functionality of the angular positioning and pressure regulation control schemes to those of a PI and P controller, respectively.

The control constants for the PID controller were manually calibrated using a common calibration procedure. In brief, the utilized procedure is as follows:

(1) Increase proportional (P) constant until controller reaches the target in an acceptable amount of time.
(2) Increase integration (I) constant until oscillations about the target point dominate system response.
(3) Reduce integration constant until stability is achieved. This step usually takes the form of a reduction in the integration constant by 10 to 25% of the value obtained in the step two.

3. RESULTS

Position Control

For PID constants of 3, 2.7, and 0 for Kp, Ki, and Kd, respectively, a closed loop feedback control system with critical damping approximately equal to one was observed. As shown in figure 7, the positioning time for the arm with an attached five pound weight is approximately 1.2 seconds. A video of the position control experiment is in reference [11]. It is important to note that slope of the line denoting the angular position verses time is not a smooth curve. This is due to the flow rate of air varying in proportion to the pressure difference existing across the actuation solenoid valves. In short, if the orifice (solenoid valve modulated via PWM) is held constant, the volumetric flow rate through the orifice will vary as the pressure difference through the most restrictive point (solenoid valve) approaches zero.

Multiple variations of the PID control constants were experimentally examined, with the listed set corresponding to lowest overshoot while still reaching the target region within a reasonable duration. As previously noted, increasing the proportional constant will cause the angular displacement to approach the target in a much shorter time period, however it will overshoot and oscillate for an unacceptable period of time (greater than 10 times that required to initially reach the target). Note that between time 0ms and 80ms the current angle does not equal the target angle; This is due to the implementation of the dead band previously mentioned, which serves as a region for which all solenoid valves are closed.

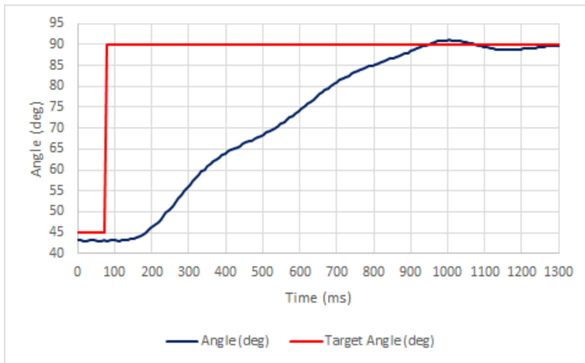


Figure 7: Position Control, Upward Stroke

Without an implemented dead band, the PID control will bring the leg into congruency with the target angle, however long period, convergent, oscillations will occur as the PID continuously overshoots and corrects in the negative and positive directions. This effect is due to the compressibility of the medium (air) and will be further expanded upon in the discussion section.

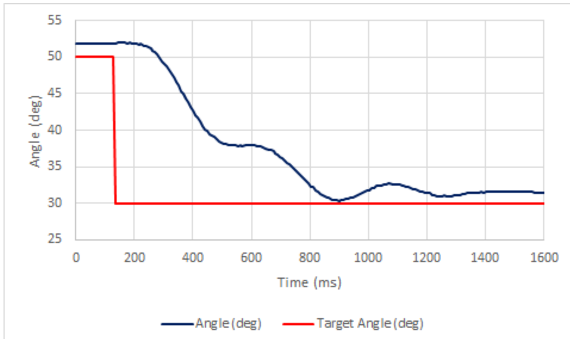


Figure 8: Position Control Downward Stroke

Conversely, when observing the downward movement of the same PID configuration previously described (fig. 8), it is first noted that the actuation speed is significantly increased over that of the upward stroke. This is due to the fact that the downward stroke is being assisted by forces due to gravity, which are causing the exhausting side of the pneumatic cylinder on a down stroke to be under a higher pressure than that of the exhausting side on the upstroke. As previously noted, with a compressible medium volumetric flow rate is proportional to the pressure difference experienced. It is therefore concluded that the downward stroke experiences a greater volumetric flow rate than the upward stroke due to this additional force.

The second noteworthy point is that which occurs at the time of 900 milliseconds (fig. 8). While the angular position does not pass below the targeted angle, a rebound occurs. This is due to the solenoids terminating the flow momentarily before the inflection point is reached, effectively causing a mass – spring system to be formed. The resulting oscillations are the result of this, as the PI controller attempts to position the leg as it oscillates beyond the confines of the dead band.

When the leg apparatus, currently in a static position, is imparted with a force impulse (Figure 9, point A), the controller is capable of restoring the leg to the same position within approximately 1500ms under the described control scheme. Such is the case when the leg is imparted with an impulse force in the form of a 25 pound weight. The leg apparatus experiences a deflection of 14% before the PID controller is able to compensate for the added mass. After a time period of one second the leg apparatus is restored to within 80% of its original position, with full restoration occurring within 1500ms. When the weight is removed (Figure 9, point B), the leg experiences a much less pronounced reaction. This is again due to the pressure differences that are experienced across the pneumatic valves.

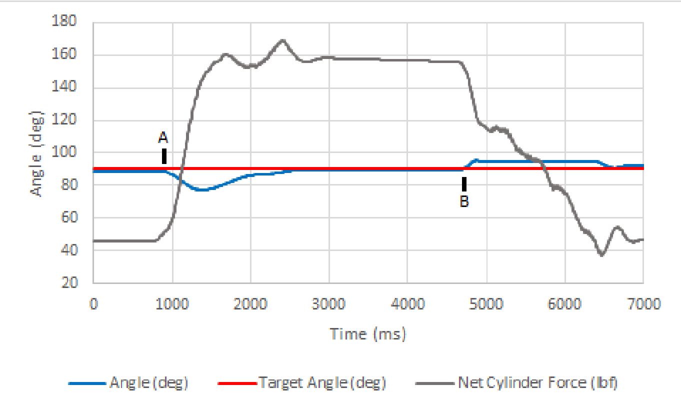


Figure 9: Effects of Impulse on the Static Apparatus

Force Control

During testing in which the control system attempts to compensate for forces exerted on the leg apparatus, effectively rendering it "weight-less", all motion is controlled by user stimulus. The test cycle consisted of two moves over the majority of the apparatus's available travel range, with the first move performed under force, while the second move is performed with as little force as possible. A video of the force control experiment is in reference [12].

As is shown in figure 10, the control loop attempts to compensate by increasing or decreasing pressure in either side of the pneumatic cylinder. The result of this is visible through direct comparison of the Extension Pressure and Retraction Pressure data sets on the associated plot. As they are approximately linear, this indicates a proportional relationship with a low resultant "Net Cylinder Force".

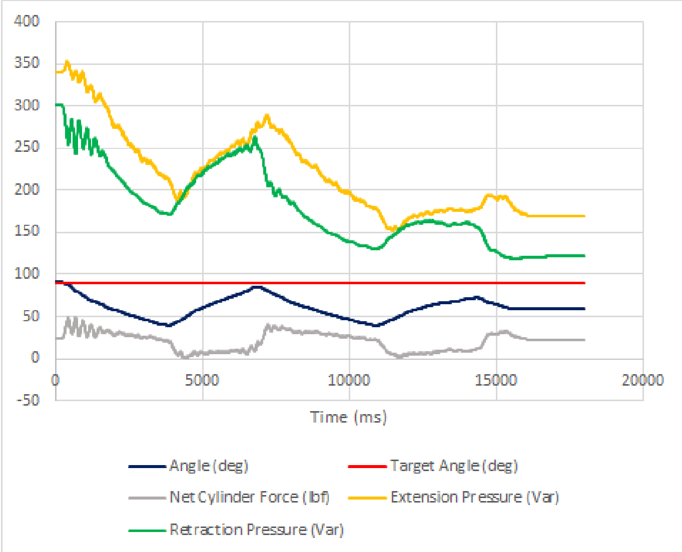


Figure 10: Force Control Compensation with User Controlled Motion (5lbm Load)

The results of this section are somewhat more evident through the examination of a constant force configuration which is loaded with a weight near the maximum that the system is capable of moving. The plot below is the same test, repeated under a 35lbm load, causing all pressure values to be exaggerated over those visible for the no load scenario.

When the system is placed under a significant load, the constant pressure relationship is clearly visible, in the form of a linear relationship between the extension and retraction pressure values. The difference in slope between the extraction pressure and retraction pressures is due to the change in relative arm lengths with respect to gravity as the angle changes. Were the torque about the knee joint not dependent on leg angle, it would be reasonable to expect the extension pressure and retraction pressure slopes to be equal in magnitude, as their difference would hold constant to maintain the leg force at a constant magnitude. The required user force to induce motion in this trial is less than five pounds of force, with little to no discernable difference depending on direction of actuation.

A variation of the constant force routine, that was specifically tuned to compensate for a 40lbm end load, was implemented. It utilizes an algorithm (Fig. 11) that equates the current angle of the leg with the required cylinder pressure differential to maintain a zero net resultant leg force. The input variable is the angular position of the leg, which is manually positioned by the user. A proportional controller then attempts to bring the net resultant leg force to zero by varying the PWM duty cycle of the control solenoids. The results of this variation are visible in Figure 12.

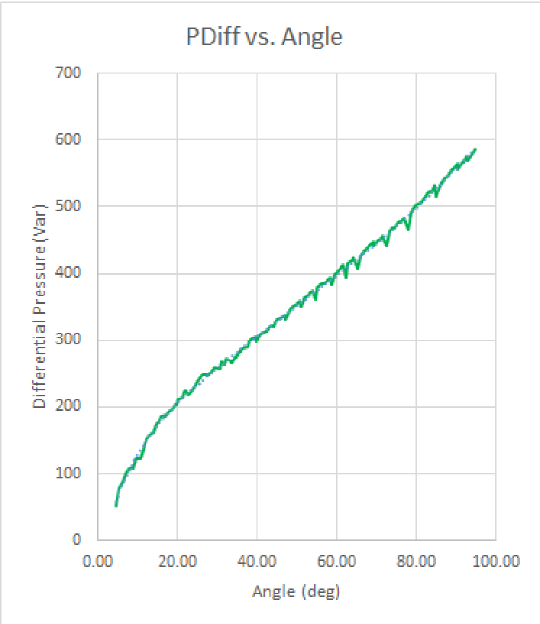


Figure 11: Constant Force, Differential (Static) Pressure vs. Leg Angle

This variation (fig. 13) provided a higher degree of compensation than that of previous versions, as the "Net Cyl. Pressure" value demonstrates. Fluctuations occur about the zero point, but do not exceed a relative value of 50 once startup transients have dissipated, indicating relatively little force is imparted on the leg by the system, beyond that required to maintain the current position. It is important to note that the weight utilized in this trial (40lb) is reaching the limit that this experimental apparatus is physically capable of controlling due to the constraints imposed by the operating pressure and diameter of the pneumatic cylinder. In fact, the retraction side (Ret Pavg) of the pneumatic cylinder is tending towards a fully actuated exhaust state, causing force compensation to be accomplished solely by the extension side of the cylinder (Ext Pavg).

The results of this variation are promising, with leg position maintained indefinitely with no discernable movement. Error due to leakage is not problematic as the control system is able to compensate for the decreases in pressure as it occurs. It is important to note that under extreme pressure and force variations, it is possible for this configuration to enter a destructive feedback loop, in which pressure variations induced by leg motion are reinforced by the controller's attempts to equate the net force. This is especially true at angles less than 20 degrees, where the damping constraints imposed by the flow of air through the control solenoids at low pressure differentials are not present. To avoid such a situation, it is advisable to implement a software based separation scheme between the angular position input and the controller to avoid reinforcing destructive movements. A simple scheme would be to disable the controller when high amplitude oscillations occur, enabling it only once the oscillations have been reduced below acceptable values.

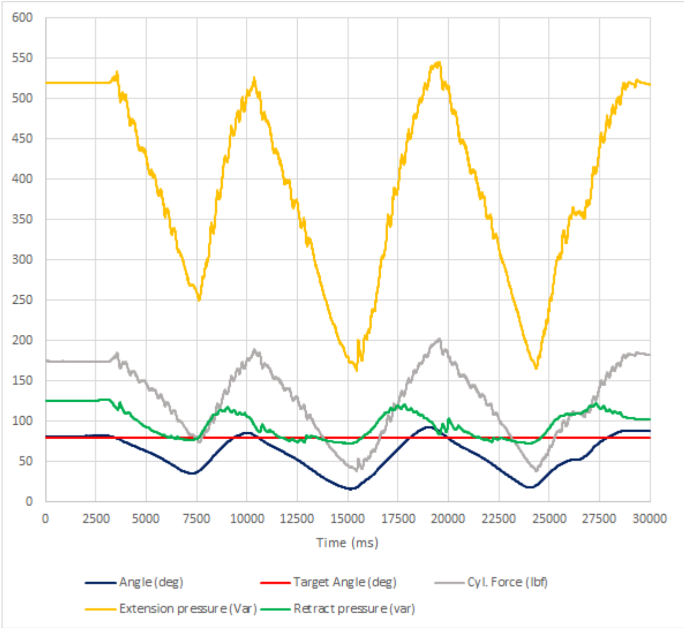


Figure 12: Force Control, Compensation with User Controlled Motion (35lbm Load)

4. DISCUSSION

As the results have shown, pneumatics are a viable candidate for the precise positioning control of a pneumatic knee joint. With a properly tuned control system, repeatable accuracy of greater than 0.1 degrees (0.05" linear) is possible, with a repeatable precision of 0.25 degrees (0.08" linear). However, at such accuracy levels, the controller transition speed will need to be sufficiently small so as to prevent oscillation about the target point, as the pneumatic cylinder will tend to act as a very close approximation of a mass-spring oscillator.

The utilization of pneumatic control systems in applications requiring force limitations, such as human interface devices, is also shown to be viable, but with limitations. Repeatability of the constant force aspect of this experiment is excellent, with little to no deviation noted between trials and a current force compensation of over 85% (Users need apply the remaining 15% to induce motion). The latter revision shows the most promise, with exceptional response and force attenuation. It does, however, possess a tendency to experience destructive oscillation during fast, high magnitude, positioning operations.

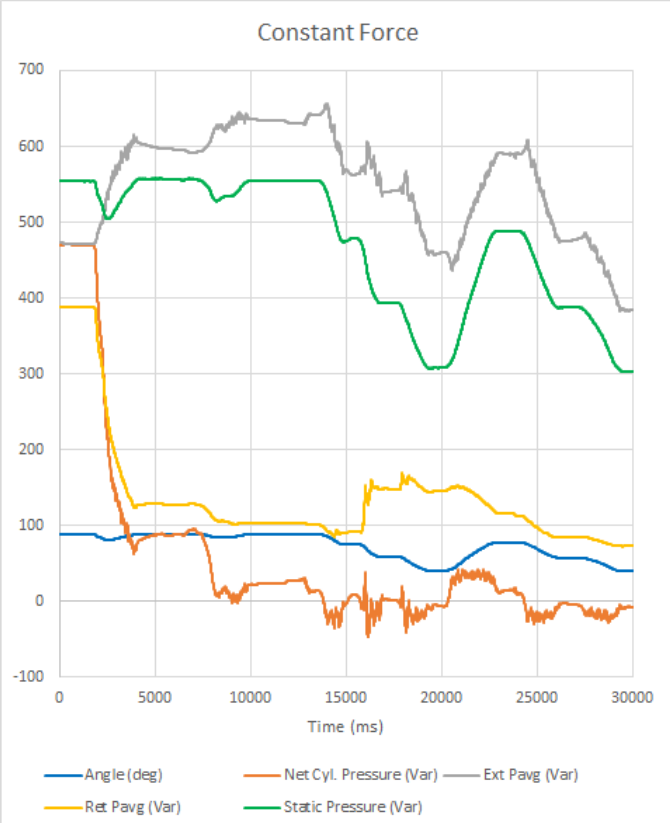


Figure 13: Force Compensation with User Controlled Motion, 40lbm end load

In addition, the results have demonstrated that operating in a negative displacement configuration (system initiates with a pressurized system and medium is released to induce motion) offers exceptional position control relative to a positive displacement configuration (movements initiate at atmospheric pressure, medium is added to induce motion). However, while the negative configuration offers increased position control and response, a positive configuration will always possess a higher transit speed at low applied forces due to the properties of the gaseous medium as it passes through the restriction points (solenoid values).

As the goal of this project was to explore the use of a PWM modulated control system, the testing apparatus was not expressly designed to mimic the physiological kinematics of the human leg. This introduces the limitation that this research, in its current form, cannot be directly applied to the immediate construction of a prosthetic device. While the settling times experienced in this report exceed those of the average human during long stride motion, future work will improve upon the control system and build from this research towards a self-contained pneumatic prosthesis.

The limitations imposed on a pneumatic control system are extensive and will be divided into two classes, general limitations and limitations specific to a certain aspect of this project. General limitations that impact pneumatic control systems are primarily related to the compressible nature of the medium. Pneumatic systems should, first and foremost, possess a supply source of sufficient flow rate to prevent large pressure variations during operation, as such variations can easily cause a formerly stable control system to become unstable as the pressures (and flow rates) drop below expected values.

Pneumatic systems that utilize PWM modulation to vary the volumetric flow rate through a standard pneumatic solenoid valve must take into account the required actuation speed and size their solenoids appropriately. While smaller solenoids will offer higher response due to the reduced mass of the electromechanical components, they will possess an extremely low system actuation rate due to flow restrictions through the valves, themselves. In addition, care must be taken to position pressure transducers as far as possible from sources of noise, such as solenoids acting under PWM modulation. The inclusion of vibration canceling design methodologies, such as restriction orifices or interference feedback loops may help alleviate noise at pressure transducer ports.

Any pneumatic system must take into account the compressibility of the medium when the method of operation is being designed. As was noted at the beginning, a positive displacement configuration will allow the highest activation rate and speed, but only when a large pressure differential exists between the medium (air) supply and the pneumatic cylinder. Whereas operating in a negative configuration causes a significant increase in the density of the medium leading to a more controllable flow rate for under high loads. Lastly, a pneumatic control system must be designed such that the maximum pressure required must never exceed one half of the maximum supply pressure. This is due to the system requiring a positive pressure differential to adequately dampen the system. Operating a pneumatic control system in such that the required pressure equals the supply pressure, would be identical to operating a car without brakes: The system will move but would be unable to stop before it hits a wall (the limit of pneumatic cylinder travel).

Limitations specific to the "defined target angle" configuration include limitations on actuation speed and frequency, as well as limitations due to the operation of the PID control scheme. The limitations on actuation speed are due both to the previously mentioned negative displacement actuation scheme and the relatively high inertia associated with the simulated leg apparatus. Methods to alleviate these limitations include increasing the pressure differential between the supply & destination and/or changing the geometry of the simulated leg so as to decrease the torque reduction ratio about the axis of rotation.

The use of a traditional PID controller demonstrated a severe inability of the controller to compensate for changing pressure differentials (medium compressibility) at the different stages of its operation. This effectively caused a PID controller, which had been tuned at one pressure, to malfunction at a different pressure. To maximize position accuracy, it is recommended that the proportional constant be set to a lower than normal level, and the integral term of the controller utilized for the bulk of movement control, as this will allow the controller to compensate in situations where the pressure differential is minimal near the end of the movement (minimal pressure differential necessitates a higher PWM duty cycle to induce the same volumetric flow rate as at higher pressure differential).

5. CONCLUSION AND FUTURE WORK

The results have shown that a pneumatic control system is a viable candidate for precise position and force control of a simulated knee joint, provided the innate limitations of the system have been taken into account. The major limitations of a pneumatic control system are an inability for the control system to compensate for impulse loading without deflection and a requirement that any control system be able to quickly compensate for changes in pressure differentials without excessive overshoot.

Future modifications to the project apparatus will include a redesign of the pressure transducer subsystem, so as to reposition the transducers in order to minimize noise due to PWM solenoid actuation. It addition, the implementation of a predictive control system, tuned to compensate for the changes in medium compressibility throughout the control cycle, may be implemented to reduce settling times to levels that better approximate those experienced by an average human during movement.

ACKNOWLEDGMENTS

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