Princeton Micro-thruster Array

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Introduction:

This project addresses the challenges faced by the NASA Origins Program, a "decades-long study addressing the origins of the universe, various astronomical bodies, and life".[1] Future missions of the program, such as the Single Aperture Far-Infrared Observatory, Terrestrial Planet Finder, and the James Webb Space telescope as well as other future space structures will need a system that can accurately position the structures in the correct orientation as well as damp induced vibrations within the structures. A microthruster array using micro-ion thrusters, micro-pulsed plasma thrusters, field emission electric propulsion, etc. would be a light and fuel efficient solution for such a problem. The aim of this specific project was to develop a proof of concept to show that such an array could be developed.

Development:

To test the model and control system of a large space structure with multiple parts a simple two armed linkage was designed. The goal of the project is to efficiently control the structure and damp oscillations or perform slew maneuvers-rotate the structure so that it maintains the same orientation but rotates to a different position. The setup, shown below, consisted of two aluminum arms each with two solenoid valves that expel CO_2 when given a signal of 12V. The CO_2 canisters are also on the arm as well as a regulator that ensures a constant pressure-thus a constant force-is expelled. Absolute rotary encoders with ball bearings were used as joints in order to read out the changing angle of the arms.

Figure 1: The Constructed Setup

[1] http://planetquest.jpl.nasa.gov/NASAorigins.cfm

Initial force calculations were done in order to ascertain both the force requirements of the valves to overcome friction and move the structure as well as the possible outputs of the parts being considered. The table below shows the thrust, mass flow rate, and friction coefficients of the final system.

Thrust	652.3 mN
Propellant Mass Flow Rate	2.6 g/s
Static Coefficient of Friction	.0145
Kinetic Coefficient of Friction	.25 kg/s

Dynamics and Control:

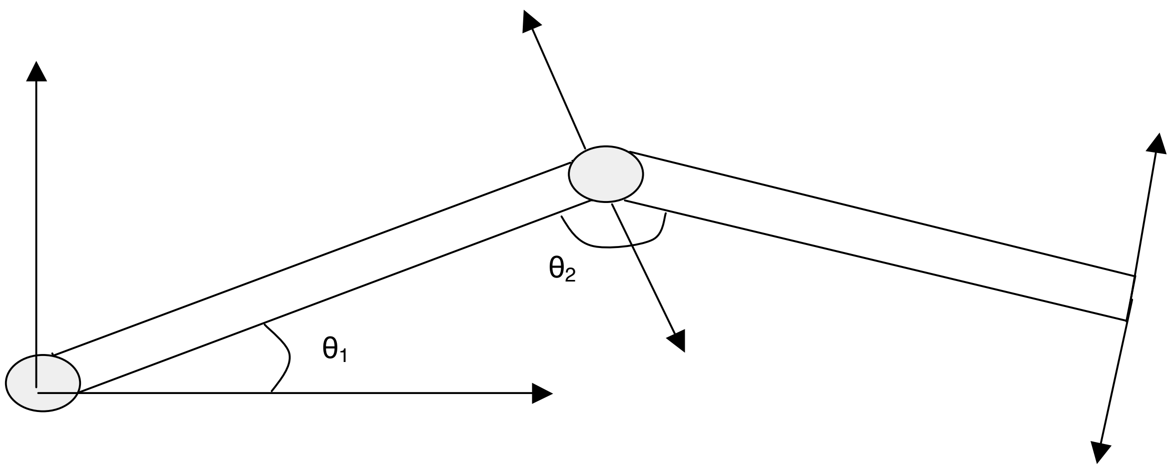


Figure 2: FBD of the Two-Armed Linkage

Although the system seems relatively simple, the dynamics are actually quite complicated. The two-armed linkage is essentially a double pendulum, a chaotic system with nonlinear dynamics. As such, the control system was greatly complicated because the standard linear models could not be used. First however, it is necessary to simulate the dynamics. The simplest way would be to linearize the system. In order for this to work the dynamics of the system would be approximated about an equilibrium point. However, this would only work for small angle deviations where the small angle approximation could be used, and thus would not work for slew maneuvers. Next, one could try to linearize the system about different points as it rotates. This method would however be ineffective as well because it would be necessary to assume a constant angular velocity, and thus not respond well to the pulsed forces and oscillations within the system.

The eventual solution for simulating the dynamics was a program in MATLAB called SimMechanics. Run with Simulink, the program allows the user to create arms, joints, supports, input forces and initial conditions and the model simulates the response of the system and outputs the resulting angles and angular velocities. The model is shown below:

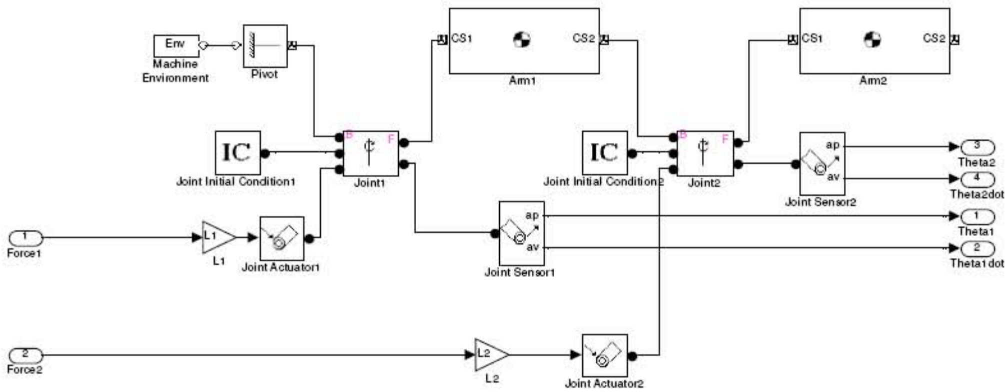


Figure 3: SimMechanics Model

This model of the system was created as a subsystem in a Simulink program that then used two proportional-integral-derivative (PID) controllers to each control one angle. Gains for the proportional, integral, and derivative terms of each control were determined by how accurately the angle needed to be followed, for example the controller for the first angle needed to rotate the structure at a low angular velocity to minimize induced oscillations so its gains were also low. In contrast the controller for the second angle maintained the initial angle between the two arms so its gains were higher. This overall system is shown below:

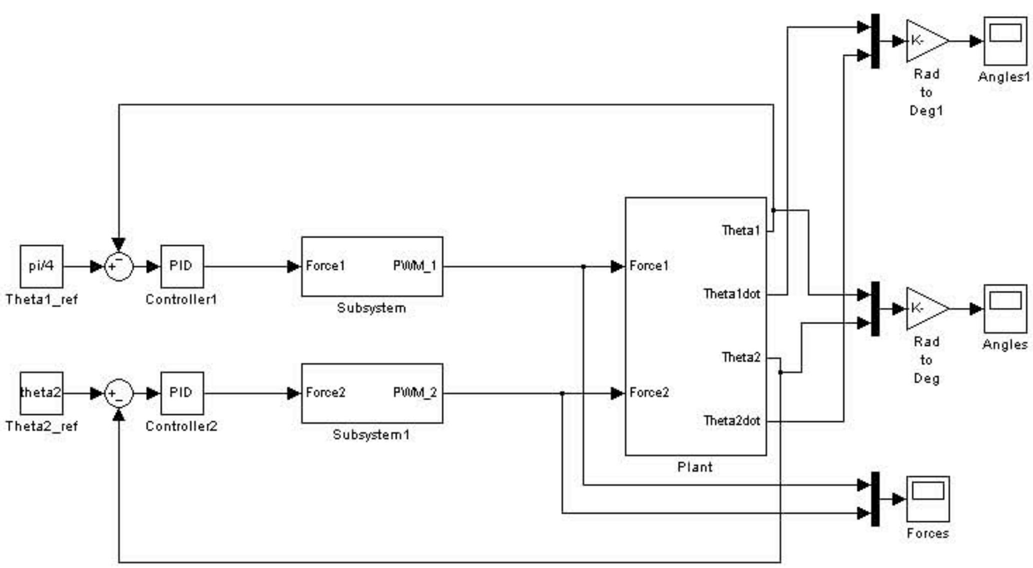


Figure 4: Simulink Control System

The control system outputs a continuous force of varying amplitude, however the solenoid valves are either open or closed, thus the force required is converted into a pulse length for a PWM signal, generated through the subsystem below:

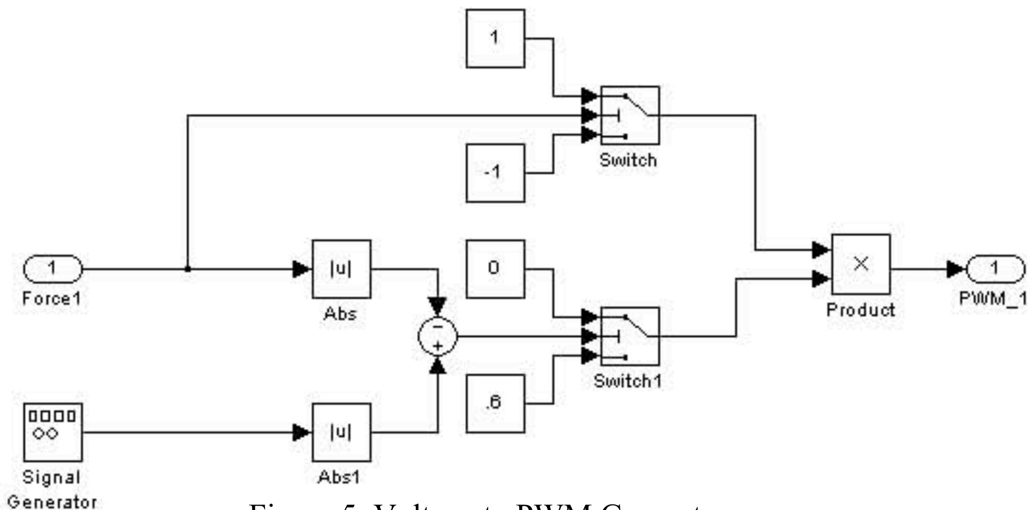


Figure 5: Voltage to PWM Generator

Results:

The program was then run in MATLAB simulating the systems response to an initial angular velocity, thus showing it damping oscillations, and the system performing a slew maneuver. In the first graph below, the structure is rotated 45 degrees with minimal oscillations in the system and while maintaining the angle between the two arms.

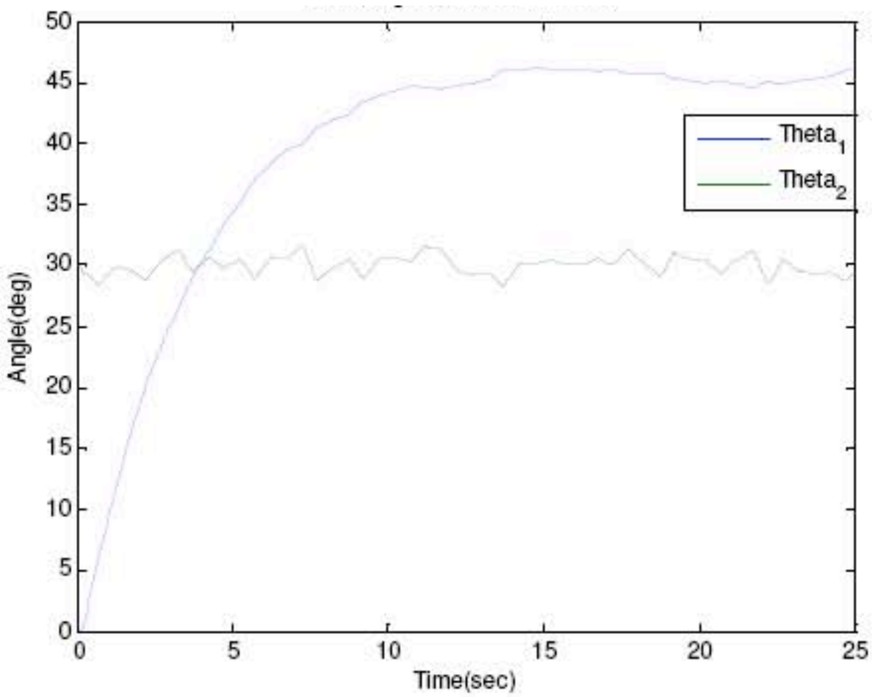
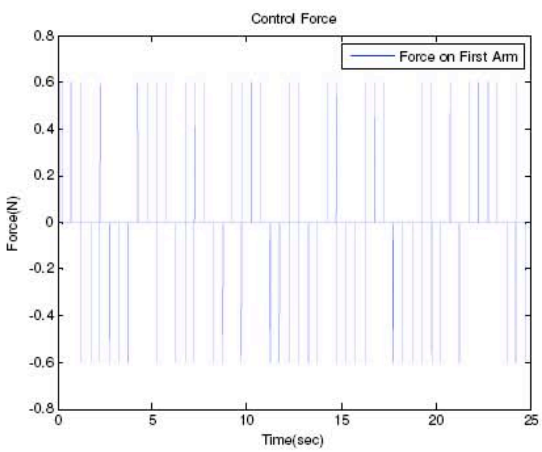
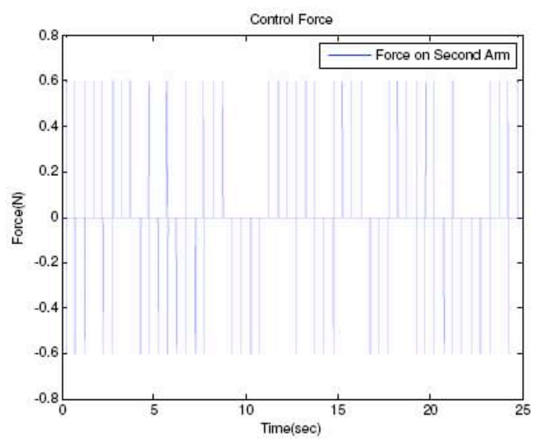


Figure 6: Rotation in θ_1 of 45 degrees

The next graph shows the control effort required in order to perform the previous maneuver





This next graph is the response of the system to an initial angular velocity. It shows how both angles are damped back to the initial state and while there is still room for improvement the system performs stably and accurately.

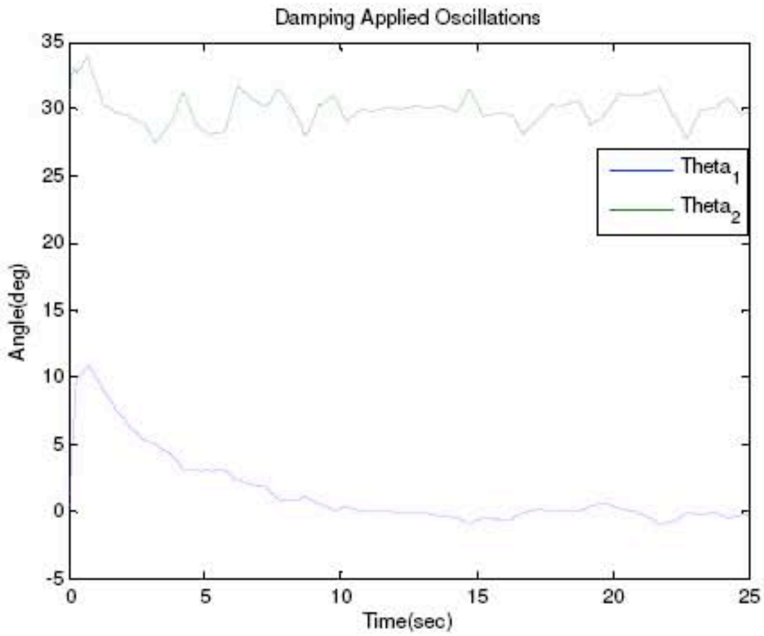


Figure 7: Response to an initial condition

The last two graphs show the control effort in order to damp out the initial angular velocity.

Conclusion:

The simulation and control of the system proved a great challenge. Because the system could not be easily modeled and controlled using linear modern control, it was necessary to use new techniques and programs to model. The Simulink model, however, proved an excellent solution. The system responded well to the PWM control and always exhitibed a stable response. The two PID controllers each controlled an angle well because the user was able to change the gains so that it met the necessary system requirements. In the future, more arms could be added to this project to simulate an even more complicated system. From there, it could even move on to a mesh to better simulate the complexities of a large and flexible space structure.