Low-Cost Control Engineering Experiments

Megan Arduin

Western Michigan University, arduinm@gmail.com

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Low-Cost Control Engineering Experiments
Megan Arduin - Jason Eichorn - Zachary Reinke
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Abstract

The disciplines found within the area of motion and controls is a vital element of each engineer’s education. The ability to understand and then control dynamic systems is a fundamental skill required for many working engineers today. The aim of this project is to further develop the tools and methods available to teach and prepare engineering students to effectively design control system architecture, and then successfully implement their design into real world systems. The main goal is to design an apparatus that can be used to teach control system methods and has an affordable price. There are few experiments where there is one overall project that can be used to teach multiple class topics from start to finish. This project was designed to be modular and easily changed to fit the topic at hand. The designs were created using a computer aided design software and then the structural components were 3D printed, thus making it easy to modify and repair. The electronic components were purchased, and the constructed models are then used to teach motion and control techniques in a thorough and engaging way adding the experience of real-world feedback to the normally theoretical control education.
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1 Introduction:

The underlying goal of this project is to design an experiment that can be built at relatively low cost. This would allow anyone with modest resources to build this system and learn about control system theory. Because the WMU Mechanical Engineering Department funds this project, the underlying goal was tailored to align with the needs of WMU. To achieve this, the design of the system will be done in correlation with the actual course material being used by the WMU faculty. It will be designed with the Motion and Control (ME-4710) Lab as the primary use, but some of the experiments may have a place within the Control Systems (ME-3600) course as well. The system designed in this project must provide a clear connection between the theoretical concepts learned in class and real world applications. The goal is to design a system that will provide strategic advantages for teaching particular control systems methods and techniques. This system will be designed with a modular approach so that new experiments can be developed using the existing system.

1.1 Background:

WMU currently offers an advanced course in motion and controls with a lab ME-4710. This course’s labs currently focus on hydraulic systems with little emphasis on electromechanical systems. Thus, there is a need to widen the focus to include electromechanical systems to better prepare the students for real world applications.

1.2 Project Objectives:

This project will seek to develop a system platform and lab procedure that will widen the range of experiments used to teach control of electromechanical systems, specifically in ME-4710. This will be achieved by designing a new electromechanical system platform. For the new system, the design focus will be on supporting WMU’s Motion and Control course curriculum. The new system’s apparatus will be built using 3D printed parts and purchased components and materials. This will make it easy to duplicate the system for multiple lab stations and to make replacement parts. The design team will focus on three main areas. The first area will focus on designing modular components that can be used to build the system platform and print it using a 3D printer. The second area will focus on utilizing the necessary tools in MATLAB and Simulink needed to implement the control system architecture designed in the lab experiment. System input is taken from sensors located on the apparatus and the output will be sent to the
device used to control the system. Once the control system architecture is designed, it can then
be deployed to a microcontroller. This will allow the control logic to run independent of the PC.
The third area of focus will be on producing a mathematical description of the system for control
system analysis.

1.3 Decision Matrix:

To help with the decision about which of the setups for the lab section would be the best
option, a decision matrix was created. The most important part of the lab is that it is helpful to
the student and that it relates directly to the course and helps to allow the student to correlate the
lab material to the real world. Another factor that the decision matrix is based on is that the lab
touched on both hydraulic and electromechanical control. The course is switching from focusing
on only hydraulic control systems to also include electromechanical control systems. Therefore,
the lab section should focus on electromechanical control but also cover hydraulic control. The
lab section should also cover both modern (state space) and classical (PID) control methods.
This will help the student once they leave college due to the fact that the company they work at
may use classical control, or they may use modern control. Due to the fact that PID is classical
control, a slightly heavier weight was placed on this requirement than modern control due to the
fact that PID is more commonly used in industry. Another factor is the flexibility of the lab
section for the instructor. This was an important part of the decision due to the fact that the
instructor wanted a way to be able to change the labs around so each semester could have a
unique sequence of labs.

Table 1: Decision Matrix

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The first option was leaving the lab with the same hydraulic labs that were previously used while only adding a few pre-designed experiments using a QUBE\(^1\) for the electromechanical experiments. The second option was to create a PID Fan Lab that could be the focus of several experiments to teach students about electromechanical control systems. For this second option, the instructor could still use some of the hydraulic experiments and the QUBE as desired. The third option was to create the same PID Fan Lab with modular parts that could be used in the design of a second system. The second system would be a helicopter, and would use some of the same parts as the PID Fan Lab. The design of the helicopter system could then be later created and tested. The third option was chosen as the best due to the modularity and flexibility of the system while still allowing both modern and classical control system methods to be taught.

1.4 Benchmarking:

To determine how necessary a new product is, it is important to research what current products there are. The main areas that were focused on with the design of this lab are the ease of use of the lab for both the student and the instructor. This allows the instructor to use the lab as an extension of the class to help the students better understand the concepts of the class. In order for this lab to be an asset to this class, the lab must be able to be used with both PID and state-space control. This allows the student to learn both classical and modern control systems. In order to help with the ease of use of the instructor, and to allow the instructor to change what system they want to use in the lab, the “kit” must be modular. Also, the price of the lab “kit” should not be high. $250 for a lab kit would be a good estimate of how expensive the lab kit is. While researching for these lab kits, it was found that there were not very many kits available. For this reason, it was determined that a lab portion of a class that had a modular lab kit, was able to work with multiple types of control, and was easy to use by both the instructor and the student would be a welcome addition to any Motion and Control class.

\(^1\) The QUANSER QUBE servo is a fully integrated device that uses a rotating pendulum to teach control concepts.
Several different control lab kits were compared as seen in Table 2. Most of the lab kits deal with PID control (classical control), but none of the kits work with state-space control (modern control). It can also be seen that while most of these kits have some ease of use, not as many are modular kits that can be changed to be used with different systems.

1.5 Facilities:

Onshape, a cloud based CAD, and MATLAB with Simulink were the primary software programs used for this project. They were chosen for their availability to WMU students, but any comparable software will work. The Innovation Club located on WMU’S main campus along with faculty mentor Dr. Meyer did all of the 3D printing for this project. The apparatus was built and assembled in the student design lab. All the testing and data collecting was done in the Parker Lab F107. While not directly used for this project, a Simulink Multibody model could be used to farther analyze the system’s dynamics. A Simulink Multibody model can be created from an Onshape assembly. This is extremely useful because the Onshape assembly includes important information such as geometry, mate relationships, and mass properties. While this can be created in Simulink without using a CAD assembly model, it can save a significant amount of time using MATLAB’s built-in functions for importing Onshape assemblies. Please see Appendix D for instructions on how to import an Onshape assembly into Simulink.
1.6 Project Timeline:

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2 Design:

2.1 Lab Apparatus Design:

This section will discuss the motion of the designed fan and helicopter PID mechanisms. Both were designed in Onshape, but because of a lack of time, only the PID Fan Lab was constructed. Most of the components were 3D printed. In order to 3D print a part, several factors must be considered in the design phase. There must be a flat side for the part to sit on while it is being printed, and it is preferable to have a base with an equal or larger size than the rest of the part. The size of the parts that can be printed is determined by the size of the printing bed available. The PID Fan Lab is shown in Figure 1 and consists of a motor, propeller, and fan shroud that are mounted on the end of an arm. The arm is held in place by a bracket. At rest, the fan lies on the table, but when the system is run, the fan lifts the arm from the table. The purchased parts include the aluminum arm, the potentiometer, the motor, the propeller, the prop adapter, and all of the screws, nuts, and bolts that hold the apparatus together.

After the initial designs were complete, the student’s safety was considered. An open propeller could be very hazardous, so the fan shroud seen in Figure 2 was created to better protect the operators.

Figure 1: PID Fan Side View

Figure 2: PID Fan Isometric View
This system can be modified to achieve more degrees of freedom by using many of the same components. One such design was created that contains two degrees of freedom. This model is a helicopter design in which the arm is mounted at its center instead of near the end. It is mounted on a pivot point that is set on top of a fixed column. A fan is then mounted on either end of the arm, one facing upward, and one facing sideways. This allows the arm to spin around as well as to tip up and down which gives this system its second degree of freedom. Most of the components from this modified design are identical to the components of the previous design. Since there are two degrees of freedom, this system requires two potentiometers to measure the position in order to create a closed loop system.

![Figure 3: Helicopter Isometric View](image)

![Figure 4: Helicopter Side View](image)

In order for the system to function properly, a satisfactory amount of torque must be available, and the chosen motor must generate enough thrust. When deciding which motor to purchase these were the main things considered. A 12-volt motor was preferred as this type of motor is very common. The motor that was chosen is a 12 volt, 17,200 revolutions per minute, DC motor.

The propeller that is used is a 10-inch-long, plastic propeller. Initially, several different sized propellers were purchased, but it was found that the 10-inch propeller was adequate for the system to work properly. A prop adapter was needed to attach the propeller to the shaft of the motor. The chosen adapter is suitable for shafts that are 3 to 6 millimeters in diameter. This adapter uses a simple nut and bolt system to hold the propeller in place and to grip the shaft of the motor.

The potentiometer that is used is a half watt, 1,000-ohm potentiometer. It was chosen because it is a very common potentiometer, and it fits the system well. In this design, it is necessary to track the angle of the fan arm. This allows for a closed loop system. There are several different methods that can be used to track an angle, but a potentiometer was chosen since it is easier to use and less expensive than an optical rotary encoder. A potentiometer functions by changing its resistance as the knob is turned. When a steady current is sent through the potentiometer, the change in voltage is measurable. By fixing the body of the potentiometer
to the base of the apparatus and forcing the knob to turn with the fan arm, the angle of the arm and the voltage at this angle can be measured. This measured voltage can then be related to this angle as shown by Equation 1. The current that is sent through the system is constant, and when the angle changes, the resistance changes linearly. In this way, the voltages are related to the different angles, and the angle of the arm is tracked by the voltage readings that are produced.

\[ V = IR \]  

\( V = \text{Voltage} \)
\( I = \text{Current} \)
\( R = \text{Resistance} \)

*Figure 5: Lab Apparatus*
Figure 6: Apparatus Base
2.2 Hardware/Software Integration:

At the core of this system is a microcontroller that interfaces the PC to the physical system that is to be controlled. The Arduino Uno microcontroller has been selected for this project. The Arduino is set to a sample rate of 1 kHz and is powered by an external 5VDC power supply. The microcontroller monitors the position of the system via the potentiometer mounted on the side of the apparatus. This information is then relayed to the PC.

![System Hardware Diagram](image)

*Figure 7: System Hardware Diagram*

After the position is read, the error is computed and the controller issues a command to a DC motor driver in the form of a pulse width modulation (PWM). PWM is a motor voltage signal in the form of a duty cycle. The Cytron MD30C R2 DC motor driver has been selected for this project. The MD30C receives PWM logic from the controller and then amplifies it to produce the desired power input to the motor. The MD30C supplies 12VDC 30A to the motor and requires a 12VCD power supply. An ABI 12V 500W is used to supply power to the motor.
driver. Error! Reference source not found. shows a block diagram of the electronic components. Please see Appendix B for detailed pictures showing the systems electronic components.

Error! Reference source not found. shows two potentiometers that are connected to the microcontroller. The first potentiometer is used to sense the angle of the apparatus. The variable voltage signal from this sensor is read by the microcontroller. The digital signal value is then mathematically manipulated to show the angle in units of degrees. This angular position information is then used for closed loop control. Similarly, the variable voltage signal from the second potentiometer is read by the controller. This signal is used for manual motor control. This allows an operator to manually control the motor to position the apparatus about a desired location. The input/output data from this manual system control is then recorded for system identification.

The Arduino is used as the interface between the PC and the system hardware. This allows Simulink to receive sensor inputs and deploy control outputs to the physical system. This also allows the computer to record and display data from the Arduino in real time. Acting as a data acquisition system, the Arduino can be used with programs like Simulink to record data. For the purpose of system analysis, the input data (voltage) and the output data (position) can be recorded in Simulink and saved to the MATLAB workspace. Figure 8 shows the system’s response (angle) to the manual motor control input (PWM).

Figure 8: Input Output
While the main use of the Arduino for this project has been to interface Simulink with the control hardware, it can also run the control logic independent of the PC. The control logic has been designed in block diagram form using Simulink. Once the Simulink models are created they can be implemented to control the apparatus in two ways. The first method allows the computer to maintain constant connection with the Arduino. This simply uses the Arduino as an interface. The second method allows the Arduino to run the control logic locally and independently of the computer.

In order to control the apparatus, control system logic must be written. There are several ways that this can be done. The most basic method would be to write the logic using the programming syntax used by the microcontroller or the computer program interfaced with the system. As previously mentioned, Simulink was used to develop the control logic for this project. Figure 9 shows one of the models created to control the apparatus. The control logic designed with Simulink can then be compiled and deployed to the Arduino if needed. See Appendix C for a detailed description of the Simulink models used in this project.

Figure 9: Simulink Closed Loop Control Model
2.3 Control System Design:

This system is designed to illustrate and teach control systems methods. Note that the control system analysis was performed on the apparatus during the build phase before the shroud was attached. Before the system can have a control systems analysis performed, the transfer functions of the system must be determined. Transfer functions are the ratios of the input variable to the output variable. The dynamics model of the apparatus was created, as seen in Figure 10 and Equation 2.

\[
\Sigma M = \ddot{\theta}l = -\dot{\theta}B - dm \cos \theta + (l - l_t)t
\]  

(2)

\[
l_{bar} = \frac{1}{3} m_{bar}l^2 - m_{bar}l_{t}l_{t} + m_{bar}l_{t}^2
\]  

(3)

\[
l_{fan} = m_{fan}(l_{f} - l_{t})^2
\]  

(4)

\[
l_{tot} = m_{fan}(l_{f} - l_{t})^2 + \frac{1}{3} m_{bar}l^2 - m_{bar}l_{t}l_{t} + m_{bar}l_{t}^2
\]  

(5)
\[(l - l_t)t = \ddot{\theta}t_{ot} + \dot{\theta}B + \left((l_f - l_t)m_{fan}g + \left(\frac{l}{2} - l_t\right)m_{bar}g\right)\cos\theta\] (6)

The equation of motion for the pendulum can be found from the dynamics model using different principles of dynamics. Once this equation of motion is found, it is linearized through a Taylor series expansion and the transfer function can be calculated as seen in Equation 7.

\[f(\theta) = \left((l_f - l_t)m_{fan}g + \left(\frac{l}{2} - l_t\right)m_{bar}g\right)\cos\theta\] (7)

\[f(\theta) \approx \left((l_f - l_t)m_{fan}g + \left(\frac{l}{2} - l_t\right)m_{bar}g\right)\cos\theta_0 + \left((l_f - l_t)m_{fan}g + \left(\frac{l}{2} - l_t\right)m_{bar}g\right)\theta_0\sin\theta_0 - \left((l_f - l_t)m_{fan}g + \left(\frac{l}{2} - l_t\right)m_{bar}g\right)\sin\theta_0 \times \theta\]

The reason the transfer function from the thrust to the position must be linearized is that it has a trigonometric equation in the equation of motion. With that trigonometric function the equation of motion cannot be analyzed using the Linear Time Invariant (LTI) methods taught. A Taylor series expansion linearizes the equation of motion so that the LTI control system analysis can be performed.

\[
\varphi \left(s^2 \left(m_{fan}(l_f - l_t)^2 + \frac{1}{3}m_{bar}l^2 - m_{bar}ll_t + m_{bar}l_t^2\right) + sB \right)
- \left((l - l_t)m_{fan}g + \left(\frac{l}{2} - l_t\right)m_{bar}g\right)\sin\theta_0
+ \left((l - l_t)m_{fan}g + \left(l_t\right)m_{bar}g + \left(\frac{l}{2} - l_t\right)m_{bar}g\right)\theta_0\sin\theta_0
\right)\left(\frac{s}{s}\right)
= (l - l_t)T
\]

\[
\frac{\varphi}{T} = \frac{As}{Ms^3 + Bs^2 - Cs + D}
\]

\[
A = l - l_t
\]

\[
M = m_{fan}(l - l_t)^2 + \frac{1}{3}m_{bar}l^2 - m_{bar}ll_t + m_{bar}l_t^2
\]

\[
B = \text{damping value}
\]
\[
C = \left( (l - l_t) m_{fan} g + \left( \frac{l}{2} - l_t \right) m_{bar} g \right) \sin \theta_0
\]
\[
D = \left( (l - l_t) m_{fan} g + \left( \frac{l}{2} - l_t \right) m_{bar} g \right) \cos \theta_0 + \left( (l - l_t) m_{fan} g + \left( \frac{l}{2} - l_t \right) m_{bar} g \right) \theta_0 \sin \theta_0
\]

The next transfer function that is needed is the voltage to angle position transfer function which is shown by Equation 10. This was found by running the system and providing a varying voltage. Once the input and output data from running the system was recorded by MATLAB, the System ID App was opened. The input and output data was imported to the system ID app. The System ID App was then used to empirically determine that a transfer function with 6 poles and 5 zeros resulted in an 84.43\% accuracy.

\[
R = \frac{-0.02561s^5 - 0.0001395s^4 - (8.325 \times 10^{-7})s^3}{s^6 + 0.2159s^5 + 0.001803s^4 + (6.372 \times 10^{-6})s^3 + (4.447 \times 10^{-8})s^2 + (3.309 \times 10^{-12})s + (2.109 \times 10^{-19})}
\]
Figure 11: System ID App

Figure 12: Input Output Data
From the voltage to position and overall plant transfer functions, the voltage to thrust transfer function as seen in Equation 11 can be found. The time delay that is part of the voltage to thrust transfer function was found by comparing the input and output in Figure 12. This time delay is 5 seconds.

Once all three transfer functions are found and the time delay is taken into consideration in the transfer function from voltage to thrust, the control system analysis can occur. Tailoring the analysis to the curriculum of ME-3600 and ME-4710, the poles and zeros, the Bode diagram, and the root locus of the system were found using MATLAB. The full MATLAB code can be found in 6.1 Appendix A: MATLAB Code.

\[
k = e^{-5s} \frac{(-1.364 \times 10^{247})s^8 - (5.361 \times 10^{248})s^7 - (2.048 \times 10^{248})s^6}{(4.73 \times 10^{248})s^5 - (2.577 \times 10^{246})s^4 - (1.534 \times 10^{244})s^3}
\]

\[
- (1.628 \times 10^{241})s^2 + (2.486 \times 10^{238})s - (3.364 \times 10^{235})}
\]

\[
.555s^7 + 0.1197s^6 + 0.0009992s^5 + (3.531 \times 10^{-6})s^4
\]

\[
+ (2.464 \times 10^{-8})s^3 + (1.945 \times 10^{-12})s^2 + (1.78 \times 10^{-16})s
\]

(11)

**Figure 13: Bode Plot for Voltage to Angular Position**

The Bode plot diagram in Figure 13 shows that the bandwidth is at $10^{-7}$ rad/sec. The bandwidth is where the magnitude of the amplitude of the Bode plot reaches -3dB from the low-frequency value.
In the Pole Zero map in Figure 14 there are two poles that are stable but the majority of the poles and zeros are marginally stable. These marginally stable points vary from stable to unstable. There is also one pole that is at the origin, this pole is unstable and causes the system to be unstable. The root locus in Figure 15 shows how the poles and zeros would change for the overall plant. The root locus shows that most of the poles and zeros could become either stable or unstable as different variables are changed.
As can be seen in the pole-zero map in Figure 17 for the thrust to position transfer function most of the zeros and poles are marginally stable (along the imaginary axis). In the root
locus seen in Figure 18, it can be seen that the poles and zeros have a tendency to become more stable as different factors are changed.

Figure 18: Root Locus Thrust to Angular Position

Figure 19: Bode Plot Voltage to Thrust
As can be seen in Figure 20, most of the poles and zeros are along the imaginary axis, and are marginally stable. From the root locus in Figure 21, it can be seen that these poles and zeros are more likely to become unstable if there were any variable changes.
It can be seen in Figure 14, Figure 17, and Figure 20 that the majority of the poles and zeros are along the imaginary axis and are therefore marginally stable. It can also be seen in the root locus diagram in Figure 18 that the thrust to position transfer function tends towards being stable, while the root locus diagram in Figure 21 shows that the transfer function from voltage to thrust tends towards being unstable. These two transfer functions combined give the transfer function from voltage to position as can be seen in Figure 15, which could become either stable or unstable depending on which variables are changed.
2.4 Project Expense:

A key feature of this system is that it is low cost. The target budget was $250. To reduce the cost in the future, fewer potentiometers could be purchased. Also, the spool of 3D Printing Filament can only be purchased in 1 kg increments. The total weight of all of the parts that were 3D printed for this device is 0.58 kg. Only the used quantity is considered in the cost analysis; however, a whole spool was purchased.

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<td>Tbymax 9V 1.5A AC/DC Power Adapter for Arduino</td>
<td>1</td>
<td>$ 7.99</td>
<td>$ 7.99</td>
</tr>
<tr>
<td>24</td>
<td>Amazon.com</td>
<td>A000073</td>
<td>Arduino Uno R3 Microcontroller</td>
<td>1</td>
<td>$ 24.95</td>
<td>$ 24.95</td>
</tr>
<tr>
<td>25</td>
<td>Amazon.com</td>
<td>32130000</td>
<td>400-Point Breadboard with Flexible Jumper Wires</td>
<td>1</td>
<td>$ 9.69</td>
<td>$ 9.69</td>
</tr>
<tr>
<td>26</td>
<td>Amazon.com</td>
<td>PLA-black</td>
<td>PLA 3D Printing Filament</td>
<td>0.58</td>
<td>$ 17.99</td>
<td>$ 10.43</td>
</tr>
</tbody>
</table>

The total cost to replicate the Fan Lab apparatus is $178.25. This price excludes all of the extra components included in the over-all project expense. At this price the cost of the lab experiment is under the target price by $71.75.
3 Data Analysis Results:

A MATLAB program was created to record the voltage and position data at a sampling frequency of 1000 Hz. The device hit the table while running. This table hit can be seen in Figure 22 in the original data where the position returns to the original position of -30 degrees before the PWM returns to 0. This table hit was taken out of the data used to find the overall plant transfer function. This was to prevent any errors that the table hit would cause, see Figure 22.

![Figure 22: Input Output Data](image)

From the recorded data, the final transfer function of the total system as seen in equation 12 was found. That transfer function was then used to find the pole-zero map, the Bode diagram, and the root locus plot as seen in Figures 23-25.

\[
R = \frac{-0.02561s^5 - 0.0001395s^4 - (8.325 \times 10^{-7})s^3}{s^6 + (9.133 \times 10^{-10})s^2 + (1.35 \times 10^{-12})s - (1.829 \times 10^{-15})} + (6.372 \times 10^{-6})s^3 + (4.447 \times 10^{-8})s^2 + (3.309 \times 10^{-12})s + (2.109 \times 10^{-19})
\] (12)
It can be seen in the pole-zero maps, figures 14, 17 and 20, for all three transfer functions that the majority of the poles and zeros are close to the imaginary axis, and therefore only marginally stable.

![Bode Diagram Voltage to Angular Position](image1.png)

*Figure 23: Bode Diagram Voltage to Angular Position*

![Pole-Zero Map Voltage to Angular Position](image2.png)

*Figure 24: Pole-Zero Map Voltage to Angular Position*

From the pole-zero map in Figure 24 and the root locus diagram in Figure 25 of the overall plant of the system, it can be seen that the majority of the poles and zeros are close to the
imaginary axis. It can also be seen that there is one pole that is at the origin, that is unstable. Leading to an unstable in which the poles and zeros could change to become more stable or more unstable if the variables were changed.

![Root Locus Voltage to Angular Position](image)

*Figure 25: Root Locus Voltage to Angular Position*

<table>
<thead>
<tr>
<th>Proportional</th>
<th>Integral</th>
<th>Derivative</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

*Table 5: Initial PID Gains*

Table 5 shows PID gains that can be used as an initial starting point. Further control design is needed to better stabilize the system. This could be done with MATLAB’s control system design toolbox.

The transfer functions that were found for this system were linearized around zero degrees, but the system could also be linearized around different angles. This would achieve more accurate transfer functions for when the device is not near the angle zero. When linearizing functions, the linearization is only accurate for a small range of degrees. To overcome this, the transfer function from thrust to position was linearized every 15 degrees. Due to the range of
positions 0-90 degrees that the apparatus can have, it was chosen to linearize every 15 degrees, which is a small range and evenly goes into 90 degrees.

Table 6: Linearization Angles

<table>
<thead>
<tr>
<th>Title of Equation</th>
<th>Linearized about (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>0</td>
</tr>
<tr>
<td>Ga</td>
<td>15</td>
</tr>
<tr>
<td>Gb</td>
<td>30</td>
</tr>
<tr>
<td>Gc</td>
<td>45</td>
</tr>
<tr>
<td>Gd</td>
<td>60</td>
</tr>
<tr>
<td>Ge</td>
<td>75</td>
</tr>
<tr>
<td>Gf</td>
<td>90</td>
</tr>
</tbody>
</table>

\[
G = \frac{0.555s}{0.1018s^3 + 4s^2 + 1.506s + 3.521}
\]

\[
Ga = \frac{0.555s}{0.1018s^3 + 4s^2 + 1.638s + 3.487}
\]

\[
Gb = \frac{0.555s}{0.1018s^3 + 4s^2 + 1.761s + 3.384}
\]

\[
Gc = \frac{0.555s}{0.1018s^3 + 4s^2 + 1.866s + 3.213}
\]

\[
Gd = \frac{0.555s}{0.1018s^3 + 4s^2 + 1.947s + 2.975}
\]

\[
Ge = \frac{0.555s}{0.1018s^3 + 4s^2 + 1.998s + 2.671}
\]

\[
Gf = \frac{0.555s}{0.1018s^3 + 4s^2 + 2.1015s + 2.305}
\]
4 Conclusion:

There are several factors of the PID Fan lab that could be improved for future use. All the electrical components of the apparatus could be outfitted with quick connect wire connections. A platform to mount all of the electrical components was designed but never printed due to time constraints. Mounting the components would ensure that the components stayed together and would keep them from getting separated from the apparatus. In the final weeks of the project the fan shroud was designed and 3D printed. After further testing with the fan shroud installed, it was shown that the added weight at the end of the pendulum caused the motor to work much harder to maintain a horizontal position. At the horizontal position the motor is near its maximum thrust capacity in order to hold the position. This makes the system slow and under-actuated. This could be improved by removing mass from the fan shroud by printing the components with a 10% fill or less.

For future work on this project, it is recommended that the helicopter lab be further developed. Many of the parts and components for the fan lab can be utilized with that design without needing to purchase additional parts. Developing the helicopter lab would also expand the experiment options for instructors to use in teaching control systems. Developing control software other than MATLAB and Simulink would benefit students who don’t have access to these expensive programs. This could be done using free programs like Octave or Scilab.
5 References:


6 Appendix:
6.1 Appendix A: MATLAB Code and Output
% Finding the transfer function from voltage to position (angle)

time=0:.001:30.674;

T=time(:);
figure('name','Simulation Plot Window','NumberTitle','off');
plot(T,Position,T,PWM);
title('Original data'),ylabel('Angular Position(deg) and PWM(V)'),...
xlabel('Time (sec)');
grid on;

P2=Position(1000:25000);
PWM2=PWM(1000:25000);
T2=T(1000:25000);
figure('name','Simulation Plot Window','NumberTitle','off');
plot(T2,P2,T2,PWM2);
title('Without the table hit'),ylabel('Angular Position(deg) and PWM(V)'),...
xlabel('Time (sec)');
grid on;
P3 = Position(8000:12000);
Pwm3 = PWM(8000:12000);
T3 = T(8000:12000);
figure('name','Simulation Plot Window','NumberTitle','off');
plot(T3, P3, T3, Pwm3);
title('Transfer function data'), ylabel('Angular Position(deg) and PWM(V)'), xlabel('Time (sec)');
grid on;
Bring up System ID App and estimate the transfer function using 6 poles and 5 zeros

\[ R = \frac{-0.02561 s^5 - 0.0001395 s^4 - 8.325e-07 s^3 - 9.133e-10 s^2 + 1.35e-12 s - 1.829e-15}{s^6 + 0.2159 s^5 + 0.001803 s^4 + 6.372e-06 s^3 + 4.447e-08 s^2 + 3.309e-12 s + 2.109e-19} \]

Continuous-time transfer function.

Finding the transfer function from thrust to position

\[
\begin{align*}
V_{\text{bar}} &= \frac{\pi \times (0.025527^2 - 0.0216916^2)}{4} \times 0.635; \\
m_{\text{bar}} &= V_{\text{bar}} \times 2700; \\
m_{\text{fan}} &= 0.276691; \\
l_{\text{bar}} &= 0.635; \\
l_{\text{tail}} &= 0.105; \\
l_{\text{fan}} &= 0.66; \\
g &= 9.81; \\
\theta_1 &= 0; \\
\theta_2 &= 0.0174533 \times \theta_1; \\
I_{\text{bar}} &= (1/3) \times (m_{\text{bar}} \times l_{\text{bar}}^2) - (m_{\text{bar}} \times l_{\text{bar}} \times l_{\text{tail}}) + (m_{\text{bar}} \times l_{\text{tail}}^2) \times ((l_{\text{bar}}/4)^2); \\
I_{\text{fan}} &= m_{\text{fan}} \times (l_{\text{fan}} - l_{\text{tail}})^2; \\
I_{\text{tot}} &= I_{\text{bar}} + I_{\text{fan}}; \\
B &= 4; \\
A &= l_{\text{fan}} - l_{\text{tail}}; \\
C &= (l_{\text{fan}} - l_{\text{tail}}) \times m_{\text{fan}} \times g + ((l_{\text{bar}}/2) - l_{\text{tail}}) \times m_{\text{bar}} \times g \times \sin(\theta_1); \\
D &= ((l_{\text{fan}} - l_{\text{tail}}) \times m_{\text{fan}} \times g + ((l_{\text{bar}}/2) - l_{\text{tail}}) \times m_{\text{bar}} \times g \times \cos(\theta_1)) \times (((l_{\text{fan}} - l_{\text{tail}}) \times m_{\text{fan}} \times g + ((l_{\text{bar}}/2) - l_{\text{tail}}) \times m_{\text{bar}} \times g \times \theta_2 \times \sin(\theta_1));
\end{align*}
\]
num = [A 0];
den = [Itot B C D];
G = tf(num,den)

G =

0.555 s
------------------------------------
0.1018 s^3 + 4 s^2 + 1.506 s + 3.521

Continuous-time transfer function.

% finding the voltage to thrust transfer function
Gi = inv(G);
Q = R*Gi*(1./(exp(-5*'s')))

Q =

-1.366e247 s^8 - 5.369e248 s^7 - 2.051e248 s^6 - 4.737e248 s^5 - 2.58e246 s^4 - 1.537e244 s^3 - 1.684e241 s^2 + 2.489e238 s - 3.375e235

-----------------------------------------------------------------------------------------------------------------------------
0.555 s^7 + 0.1198 s^6 + 0.001001 s^5 + 3.537e-06 s^4 + 2.468e-08 s^3 + 1.836e-12 s^2 + 1

Continuous-time transfer function.

[num2,den2] = tfdata(Q, 'v');
% The transfer function from voltage to thrust including the time delay
Q2=tf(num2,den2,'InputDelay',5)

Q2 =

-1.366e247 s^8 - 5.369e248 s^7 - 2.051e248 s^6 - 4.737e248 s^5 - 2.58e246 s^4 - 1.537e244 s^3 - 1.684e241 s^2 + 2.489e238 s - 3.375e235

exp(-5*s) *-----------------------------------------------------------------------------------------------------------------------------
0.555 s^7 + 0.1198 s^6 + 0.001001 s^5 + 3.537e-06 s^4 + 2.468e-08 s^3 + 1.836e-12 s^2 + 1

Continuous-time transfer function.

%Control Analysis of Voltage to position

%bode diagram
figure('name','Simulation Plot Window','NumberTitle','off');
bode(R),grid;
title('Bode Diagram voltage to angular position');
grid on;
% poles and zeros
figure('name','Simulation Plot Window','NumberTitle','off');
pzmap(R);
grid on;
title('Pole-Zero Map voltage to angular position'),ylabel('Imaginary Axis (1/sec)')...
xlabel('real Axis(1/sec)');
grid on;
zeros = roots(tf1.Numerator)

zeros =
  -0.0020 + 0.0050i
  -0.0020 - 0.0050i
  -0.0026 + 0.0000i
  0.0006 + 0.0008i
  0.0006 - 0.0008i

poles = roots(tf1.Denominator)

poles =
  -0.2074 + 0.0000i
  -0.0081 + 0.0000i
  -0.0002 + 0.0051i
  -0.0002 - 0.0051i
  -0.0001 + 0.0000i
  -0.0000 + 0.0000i

%root locus
figure('name','Simulation Plot Window','NumberTitle','off');
rlocus(R);
title('Root Locus voltage to angular position'),ylabel('Imaginary Axis (1/sec)')...
  ,xlabel('real Axis(1/sec)');
grid on;
Control Analysis of thrust to position

% Control of thrust to position
% Bode diagram
figure('name','Simulation Plot Window','NumberTitle','off');
bode(G), grid;
title('Bode Diagram thrust to angular position');
grid on;
```matlab
%poles and zeros
figure('name','Simulation Plot Window','NumberTitle','off');
pzmap(G);
grid on;
title('Pole-Zero Map thrust to angular position'),ylabel('Imaginary Axis (1/sec)')
,xlabel('real Axis(1/sec)');
grid on;
```
zeros = roots(num)
zeros = 0

poles = roots(den)
poles =
-38.9303 + 0.0000i
-0.1786 + 0.9255i
-0.1786 - 0.9255i

% root locus
figure('name','Simulation Plot Window','NumberTitle','off');
rlocus(G);
title('Root Locus thrust to angular position'),ylabel('Imaginary Axis (1/sec)')...
xlabel('real Axis(1/sec)');
grid on;
%Control Analysis of Voltage to thrust

%bode diagram
figure('name','Simulation Plot Window','NumberTitle','off');
bode(Q),grid;
title('Bode Diagram voltage to thrust');
grid on;
% poles and zeros
figure('name','Simulation Plot Window','NumberTitle','off');
pzmap(Q);
grid on;
title('Pole-Zero Map voltage to thrust'),ylabel('Imaginary Axis (1/sec)')...
 ,xlabel('real Axis(1/sec)');
grid on;
zeros = roots(num2)

zeros =
-38.9303 + 0.0000i
-0.1786 + 0.9255i
-0.1786 - 0.9255i
-0.0020 + 0.0050i
-0.0020 - 0.0050i
-0.0026 + 0.0000i
0.0006 + 0.0008i
0.0006 - 0.0008i

poles = roots(den2)

poles =
0.0000 + 0.0000i
-0.2074 + 0.0000i
-0.0081 + 0.0000i
-0.0002 + 0.0051i
-0.0002 - 0.0051i
-0.0001 + 0.0000i
-0.0000 + 0.0000i

%root locus
figure('name','Simulation Plot Window','NumberTitle','off');
rlocus(Q);

Warning: Accuracy may be poor in parts of the frequency range. Use the "prescale" command to maximize accuracy in the range of interest.

title('Root Locus voltage to thrust'),ylabel('Imaginary Axis (1/sec)')...,
xlabel('real Axis(1/sec)');
grid on;

%If the thrust to position transfer function would be linearized around other angles than 0, the transfer function would be as follows.
%15 degrees
theta1e = 15;
theta2e = 0.0174533.*theta1e;

Cd=(lfan-ltail).*mfan.*g+((lbar./2)-ltail).*mbar.*g.*sind(theta1e);
Dd=(((lfan-ltail).*mfan.*g+((lbar/2)-ltail).*mbar.*g.*theta2e.*sind(theta1e))...
+((lfan-ltail).*mfan.*g+((lbar/2)-ltail).*mbar.*g.*theta2e.*sind(theta1e));

num = [A 0];
den = [Itot B Cd Dd];
Ga = tf(num,den)

Ga =

0.555 s

------------------------------------
0.1018 s^3 + 4 s^2 + 1.638 s + 3.487

Continuous-time transfer function.

If Linearized around 15 degrees

%30 degrees
theta1b = 30;
theta2b = 0.0174533.*theta1b;
$Cb = (lfan-ltail) \cdot mfan \cdot g \cdot ((lbar/2)-ltail) \cdot mbar \cdot g \cdot \sin(\theta_1b)$;
$Db = (((lfan-ltail) \cdot mfan \cdot g \cdot ((lbar/2)-ltail) \cdot mbar \cdot g \cdot \cos(\theta_1b))...
+((lfan-ltail) \cdot mfan \cdot g \cdot ((lbar/2)-ltail) \cdot mbar \cdot g \cdot \theta_2b \cdot \sin(\theta_1b)));
$
num = [A \ 0];
den = [Itot \ B \ Cb \ Db];
Gb = tf(num,den)$

\[
Gb =
\begin{align*}
0.555 \text{ s} \\
0.1018 s^3 + 4 s^2 + 1.761 s + 3.384
\end{align*}
\]
Continuous-time transfer function.

If linearized around 30 degrees

\[
\%45 \text{ degrees}
\]
\[
\theta_1c = 45;
\theta_2c = 0.0174533 \cdot \theta_1c;
\]
$Cc = (lfan-ltail) \cdot mfan \cdot g \cdot ((lbar/2)-ltail) \cdot mbar \cdot g \cdot \sin(\theta_1c)$;
$Dc = (((lfan-ltail) \cdot mfan \cdot g \cdot ((lbar/2)-ltail) \cdot mbar \cdot g \cdot \cos(\theta_1c))...
+((lfan-ltail) \cdot mfan \cdot g \cdot ((lbar/2)-ltail) \cdot mbar \cdot g \cdot \theta_2c \cdot \sin(\theta_1c)));
$
num = [A \ 0];
den = [Itot \ B \ Cc \ Dc];
Gc = tf(num,den)$

\[
Gc =
\begin{align*}
0.555 \text{ s} \\
0.1018 s^3 + 4 s^2 + 1.866 s + 3.213
\end{align*}
\]
Continuous-time transfer function.

If linearized around 45 degrees

\[
\%60 \text{ degrees}
\]
\[
\theta_1d = 60;
\theta_2d = 0.0174533 \cdot \theta_1d;
\]
$Cd = (lfan-ltail) \cdot mfan \cdot g \cdot ((lbar/2)-ltail) \cdot mbar \cdot g \cdot \sin(\theta_1d)$;
$Dd = (((lfan-ltail) \cdot mfan \cdot g \cdot ((lbar/2)-ltail) \cdot mbar \cdot g \cdot \cos(\theta_1d))...
+((lfan-ltail) \cdot mfan \cdot g \cdot ((lbar/2)-ltail) \cdot mbar \cdot g \cdot \theta_2d \cdot \sin(\theta_1d)));
$
num = [A \ 0];
den = [Itot \ B \ Cd \ Dd];
Gd = tf(num,den)$

\[
Gd =
\begin{align*}
0.555 \text{ s} \\
0.1018 s^3 + 4 s^2 + 1.947 s + 2.975
\end{align*}
\]
Continuous-time transfer function.

If linearized around 60 degrees

% 75 degrees
theta1e = 75;
theta2e = 0.0174533.*theta1e;

Ce = (lfan-ltail).*mfan.*g + ((lbar/2)-ltail).*mbar.*g.*sind(theta1e);
De = (((lfan-ltail).*mfan.*g + ((lbar/2)-ltail).*mbar.*g).*coshd(theta1e)) + ...
((lfan-ltail).*mfan.*g + ((lbar/2)-ltail).*mbar.*g.*theta2e.*sind(theta1e));

num = [A 0];
den = [Itot B Ce De];
Gf = tf(num,den);

Gf =

0.555 s
------------------------------------
0.1018 s^3 + 4 s^2 + 1.998 s + 2.671

Continuous-time transfer function.

If linearized around 75 degrees

% 90 degrees
theta1f = 90;
theta2f = 0.0174533.*theta1f;

Cf = (lfan-ltail).*mfan.*g + ((lbar/2)-ltail).*mbar.*g.*sind(theta1f);
Df = (((lfan-ltail).*mfan.*g + ((lbar/2)-ltail).*mbar.*g).*coshd(theta1f)) + ...
((lfan-ltail).*mfan.*g + ((lbar/2)-ltail).*mbar.*g.*theta2f.*sind(theta1f));

num = [A 0];
den = [Itot B Cf Df];
Gf = tf(num,den);

Gf =

0.555 s
------------------------------------
0.1018 s^3 + 4 s^2 + 2.015 s + 2.305

Continuous-time transfer function.

If linearized around 90 degrees
6.2 Appendix B: Circuit Layout
6.3 Appendix C: Simulink Models

Two different Simulink models are used when working with the apparatus. A model was created specifically to capture data for system identification analysis. This model allows an operator to manually control the motor to position the apparatus about a desired location. The input/output data from this manual system control is then recorded for system identification. Figure 28 shows the Simulink model used to capture I/O data. Pin 0 reads the variable voltage from the manual control potentiometer. This signal is then mathematically manipulated and used to command a PWM to the motor driver via pin 10. A “To Workspace” block labeled “PWM” takes the PWM signal and saves it to the MATLAB workspace for further analysis. Pin 2 reads the variable voltage from the potentiometer mounted to the side of the apparatus. This reads the position of the pendulum. This signal is then mathematically manipulated to show position in units of degrees. Note that 0 degrees is measured at the horizontal axis. A “To Workspace” block labeled “Position” takes the position signal and saves it to the MATLAB workspace for further analysis. The data saved to the workspace is recorded at a sample rate of 1 kHz.

A second Simulink model is used to implement closed control on the system. This model uses a simple closed loop with a constant reference value, PID controller, and a system IO subsystem. Figure 29 shows the Simulink model used for closed loop control. Figure 30 shows the system IO subsystem, labeled Arduino IO, that contains the logic that interfaces with the apparatus. Pin 2 reads the variable voltage from the potentiometer mounted to the side of the apparatus. This reads the position of the pendulum. This signal is then mathematically manipulated to show position in units of degrees and routed out to the main subsystem via port1.

![Simulink Model - System ID Data Capture](image1)

Figure 26 Simulink Model - System ID Data Capture
Pin 2 outputs a constant logic low signal. This is a control requirement of the motor driver. Port1 {in} receives the signal from the PID controller and routes it into pin 10 that outputs the PWM logic to the motor driver.

Figure 27 Simulink Model - Closed Loop Control

Figure 28 Simulink Model - IO Subsystem

To set the PID gains click on the PID controller block and input the values. Once the Simulink models are created they can be used to control the system. There are two methods to choose from. The first method allows the computer to maintain constant connection with the Arduino. This allows the computer to record and display data from the Arduino in real time. This uses the Arduino as an interface between the system and the PC allowing Simulink to control the
system. To do this simply set the time limit to “inf”, set the control type to “external”, and select the play button. Press the stop button to stop the connection between the Arduino and the computer. The second method compiles the Simulink model data into code and downloads the code to the Arduino to run independently of the computer. To do this, simply click on the port icon and select “deploy to hardware”.
6.4 Appendix D: Onshape/ Simulink Import
Import Onshape assembly into Simulink.

1. Login to your Onshape account.

2. Navigate to the assembly that you wish to import and copy the URL.
3. Open Matlab and run the following commands.

```matlab
url = 'your assembly url'
xmlFile = smexportonshape(url);
smimport(xmlFile);
```

After this code is run Simulink will automatically open with the imported assembly.
6.5 Appendix E: Lab Procedure
Lab #: PID Fan Lab Data Capture

Introduction
The focus of this lab is…

Components
- Fan Apparatus
- Microcontroller board
- Microcontroller power supply
- Motor controller
- Motor controller power supply
- Computer with Simulink
Procedure – Capturing I/O Data with Simulink

1. Plug in the motor controller and Arduino power supplies.
2. Plug the USB cable from the Arduino into the computer.
3. Start MATLAB.
4. From the MATLAB home tab select Simulink.
5. From the Simulink start page click on the “open” button and navigate to the folder titled “PID Fan Lab” and select “PID_Fan_Lab_DataCapture.slx”.

6. Ensure that the motor control knob is turned all the way counterclockwise.
7. Click the “Play” button at the top of the Simulink model.
8. A code generation report will appear indicating that MATLAB has finished compiling the code. Click “Ok” to continue.
9. Once the systems status reads “Running the model on Arduino Uno” the system is live and ready for input.
10. Turn the manual motor control knob clockwise until the motor blade begins to spin. Continue to adjust the control knob until the apparatus is in the desired position. (Note that 0 degrees is measured at the horizontal axis).
11. While holding the desired position slowly (the system is sensitive) oscillate the motor control knob to simulate a small input disturbance.
12. After 20 seconds click on the “Stop” button at the top of the Simulink model.
13. Press the reset button located on the Arduino.
14. The I/O data is now saved to the MATLAB workspace. The input is saved as “PWM” and the output is saved as “Position”.

Figure 1 Simulink Model - Data Capture

Figure 2 Arduino Uno Circuit Board
Questions

1. Question 1
2. Question 2
Lab #: PID Fan Lab System ID

Introduction
The focus of this lab is…

Components
- Fan Apparatus
- Microcontroller board
- Microcontroller power supply
- Motor controller
- Motor controller power supply
- Computer with Simulink
Procedure – Modeling

Dynamics Model
1. Create the dynamics model of the apparatus
2. Use Dynamics to find the equation of motion
   \[ \Sigma M = \hat{\theta} \dot{l} = -\theta B - dm \cos \theta + (l_1 - l_t)T \]
3. Linearize the equation of motion about the desired angular position
4. Use linearized equation of motion to create the thrust to angular position transfer function.

MATLAB System ID
1. Open MATLAB
2. Save the PWM and Position Data in the Current Folder.
3. Open the PWM and Position Data in the Workspace. This can be done by double clicking the names of the PWM and the Position data files in the Current Folder dialog box in MATLAB.
4. Create a time vector that starts at 0 seconds and increases by .001 seconds to 20 seconds. The time vector should increase by .001, because the sampling frequency is at 1000 Hz.
5. The time vector will then need to be changed from a row vector to a column vector. This is so that the PWM and Position data that are in column vectors can be plotted with the time vector.
6. Plots can then be created with the time vector and the PWM and Position data.
7. If there is a long time between 0 seconds and the first voltage applied, or the device hit the table so the angle stops before the voltage, those data points can be removed from the data set.
8. The PWM and Position data were collected around a desired angle. This is to allow for the transfer function to be found using the system ID app.
9. Open the System ID app in MATLAB
10. Import the PWM data as input and the Position data as Output.
11. Estimate the transfer function. To find the transfer function with the best fit, try several combinations of the number of poles and zeros. Start with 6 poles and 5 zeros. The model output option will give a plot of the transfer function laid over the actual data.
12. Export the transfer function with the best fit to the workspace.
13. To retrieve the transfer function from the block in the MATLAB workspace, right click the block to determine the names of the numerator and the denominator.
14. Then create a transfer function in MATLAB using those numerator and denominator names.
15. The transfer function of the thrust to position can be added to the MATLAB code.
16. Using the overall plant transfer function and the thrust to position transfer function (linearized about the desired angle that the data was collected at) the Transfer function from the voltage to the thrust can be found.
17. The pole-zero map, the bode plot, and the root locus plot can then be created in MATLAB.
18. Analyze these plots.
Questions
1. Question 1
2. Question 2
ME/ECE 4710 Motion and Control

Lab #: PID Fan Lab

Introduction
The focus of this lab is…

Components
- Fan Apparatus
- Microcontroller board
- Microcontroller power supply
- Motor controller
- Motor controller power supply
- Computer with Simulink
Procedure – Running the PID Controller

1. Plug in the motor controller and Arduino power supplies.
2. Plug the USB cable from the Arduino into the computer.
3. Start MATLAB.
4. From the MATLAB home tab select Simulink.
5. From the Simulink start page click on the “open” button and navigate to the folder titled “PID Fan Lab” and select “PID_Fan_Lab_Run.slx”.
6. Click on the PID control block and enter the PID values and click “Ok”.
7. Click the “Play” button at the top of the Simulink model.
8. A code generation report will appear indicating that MATLAB has finished compiling the code. Click “Ok” to continue.
9. Once the systems status reads “Running the model on Arduino Uno” the motor will start to spin and the controller will begin to control the apparatus (Note that 0 degrees is measured at the horizontal axis).
10. After 20 seconds click on the “Stop” button at the top of the Simulink model.
11. Press the reset button located on the Arduino.

Figure 1 Simulink Model - PID Control

Figure 2 Arduino Microcontroller
Questions

1. Question 1
2. Question 2
## Appendix F: Apparatus Components

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<tr>
<th>#</th>
<th>Part #</th>
<th>Qty</th>
<th>Description</th>
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<td>Base Plate</td>
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<tr>
<td>2</td>
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<td>2</td>
<td>Joint Vertical Sides</td>
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<td>Joint Brace Clearance</td>
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<td>4</td>
<td>WMUSDIP FL-004</td>
<td>1</td>
<td>Joint Brace Thread</td>
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<td>5</td>
<td>WMUSDIP FL-005</td>
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<td>Motor Mount Base</td>
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<tr>
<td>6</td>
<td>WMUSDIP FL-006</td>
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<td>Motor Mount Strap</td>
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<td>Potentiometer Mount</td>
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<td>8</td>
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<td>Potentiometer Adapter</td>
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<td>Stop</td>
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Note: STL Parts saved with units of mm
6.7 Appendix G: ABET Questionnaire

Form 1
To be completed by student

Assessment of Student Outcome # c
ME 4800

“An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political ethical, health and safety, manufacturability, and sustainability” is listed in ABET General Criterion 3. Student Outcomes as one of the student outcomes to be assessed for both Mechanical and Aerospace Engineering programs. As part of your design project, you are required to fill out this form and include it in your ME4800 Final Report, please include the page numbers where the questions following are addressed.

Evaluation of student outcome “An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political ethical, health and safety, manufacturability, and sustainability”

1. This project involved the design of a: system / component / process
   Description: This project involved a system that has the purpose of helping to teach control system methods.

2. The need: This project was needed because WMU needed to upgrade their Motion and Controls Lab to include electromechanical systems.

3. The constraints: (discuss the constraints that were relevant to the project. At least 3 constraints must be addressed.)

   Economic: There was an economical constraint to this project due to the fact that one purpose of the system is to be a low cost way to help teach control methods. In order to keep this low cost the budget was around $250-$300.

   Environmental: N/A

   Social: N/A

   Political:
Ethical:

Health & Safety:
This system will be used at the university in a lab that students will participate in. This means that the safety of the person running the system and the safety of the students watching the lab must be considered. Due to the spinning propeller a guard had to be designed for safety purposes.

Manufacturability:
Due to the fact that most of this system was 3D printed and the only 3D printers that were accessible had limited printing area, when the system was designed the manufacturability of the pieces had to be taken into consideration.

Sustainability:

Others:

4. Is there a potential for a new patent in your design? Explain and compare to similar patents.

There is no potential for a new patent for this design.
Form 2  
To be completed by student 

Assessment of Student Outcome #j 
ME 4800

“A knowledge of contemporary issues” is listed in ABET General Criterion 3. Student Outcomes as one of the student outcomes to be assessed for both Mechanical and Aerospace Engineering programs. The Mechanical Engineering Faculty Members have defined “A knowledge of contemporary issues” as knowledge and application of new technologies or recent innovations, satisfaction of the company’s existing customers, comparison of the proposed design with the competitor’s products, well-being and performance of other employers, safety and legal issues, new standards or recent product regulations, and possibility of product patent. As you work on your senior design project, we ask you to answer the following questions. These questions will help you to create the ideas needed to successfully complete your project and hence your ME4800 final report. You are required to fill out this form and submit it with your final report. Please include the page numbers where the following questions are addressed.

Evaluation of student outcome “A knowledge of contemporary issues”

1. Why is this project needed now?

This project was needed now because WMU needed to upgrade their Motion and Controls Lab to include electromechanical systems.

2. Describe any new technologies and recent innovations utilized to complete this project and how will it improve satisfaction of the company’s existing customers?

The technology that was used was MATLAB, Simulink, CAD systems, and Arduino controllers.

3. If this project is done for a company – how will it expand their potential markets?

N/A

How will it improve satisfaction of the company’s existing customers?

N/A

Identify the competitors for this type of product, and compare the proposed design with the products of the company’s competitors.
4. How did you address any safety and/or legal issues pertaining to this project? (e.g., OSHA, EPA, Human Factors, etc.)

Safety issues were overcome by adding a fan shroud to the propeller.

5. Are there any foreseeable future standards or regulations on the horizon that could impact the development of the project?

There are no new standards or regulations that will impact this project.


There is no potential for a new patent for this design.
Form 3  
To be completed by student  

Assessment of Student Outcome # h  
ME 4800  

“An understanding of the impact of engineering solutions in a global, environmental and societal context” is listed in ABET General Criterion 3. Student Outcomes as one of the student outcomes to be assessed for both Mechanical and Aerospace Engineering programs. As you work on your senior design project, we ask you to answer the following questions. These questions will help you to create the ideas needed to successfully complete your project and hence your ME4800 final report. You are required to fill out this form and submit it with your final report. Please include the page numbers where the following questions are addressed.

Evaluation of student outcome “An understanding of the impact of engineering solutions in a global, environmental and societal context”

1. Is this project useful outside of the United States? Explain why.  
Yes, this is useful outside of the United States. This is because control systems are universal concepts.  

2. Does your project comply with U.S. and/or international standards or regulations?  
Which standards are applicable?  
Unsure what regulations this lab redesign would fall under, if any.  

3. Is this project restricted in its application to specific markets or communities? To which markets or communities?  
This project is restricted to technical training markets. The markets and communities would be Universities and Colleges.  

4. If the answer to any of the following items is affirmative, explain how and where, when relevant. What actions did you take to address the issues?  

Design is focused on serving human needs. Design also can either negatively or positively influence quality of life. Address the impact of your project on the following areas.
Air Quality?
N/A

Water Quality?
N/A

Food?
N/A

Noise Level?
Noise Level is low. All noise is produced by small DC motors and small propellers.

Does the project impact:

**Human health?**
No, this project does not impact human health.

**Wildlife?**
No, this project does not impact wildlife.

**Vegetation?**
No, this project does not impact vegetation.

Does this project improve:

**Human interaction?**
No, this project does not improve human interaction.

**Well-being?**
No, this project does not improve well-being.

**Safety?**
No, this project does not improve safety.

**Others?**
This project will improve the knowledge of control system techniques in industry.
Assessment of Student Outcome # i

ME 4800

“A recognition of the need for, and ability to engage in life-long learning” is listed in ABET General Criterion 3. Student Outcomes as one of the student outcomes to be assessed for both Mechanical and Aerospace Engineering programs. As you work on your senior design project, we ask you to answer the following questions. These questions will help you to create the ideas needed to successfully complete your project and hence your ME4800 final report. You are required to submit the completed form in the last appendix of your final report. Your responses will be used in the Evaluation of student outcome “A recognition of the need for, and ability to engage in life-long learning.”

A well-organized team brings together the necessary backgrounds and talents needed to successfully develop and complete the design process. Each team member plays an important role on the design team. Team members must be prepared to acquire any new additional skills, and improve existing ones during the development of the project. Your answers to the questions below will be used to evaluate a) your understanding of the need for life-long learning and b) your ability to recognize the need of acquiring new knowledge/skills when required.

NAME: Megan Arduin

• List the skills you needed to execute your responsibilities on the project as outlined in ME 4790.

The skills necessary for me to execute this project were knowledge of Control systems, some CAD modeling, building block diagrams in Simulink, and using MATLAB to perform some of the control analysis, also dynamics to find the dynamic model of the thrust of the fan to the position.

• Explain how you acquired or improved the skills needed for the completion the project.

I acquired these skills by taking the time to learn the skills that I did not know, or to relearn the skills that I was no longer very familiar with. I used online resources and also class notes to be able to gain strength in the areas that I needed to improve my skills.

Form 4
To be completed by student

Assessment of Student Outcome # i

ME 4800

“A recognition of the need for, and ability to engage in life-long learning” is listed in ABET General Criterion 3. Student Outcomes as one of the student outcomes to be assessed for both Mechanical and Aerospace Engineering programs. As you work on your senior design project, we ask you to answer the following questions. These questions will help you to create the ideas needed to successfully complete your project and hence your ME4800 final report. You are required to submit the completed form in the last appendix of your final report.

Your responses will be used in the Evaluation of student outcome “A recognition of the need for, and ability to engage in life-long learning.”

A well-organized team brings together the necessary backgrounds and talents needed to successfully develop and complete the design process. Each team member plays an important role on the design team. Team members must be prepared to acquire any new additional skills, and improve existing ones during the development of the project. Your answers to the questions below will be used to evaluate a) your understanding of the need for life-long learning and b) your ability to recognize the need of acquiring new knowledge/skills when required.

ME 4800

Mechanical and Aerospace Engineering Design Project

For each team member:

NAME: Jason Eichorn

• List the skills you needed to execute your responsibilities on the project as outlined in ME 4790.

The necessary skills for me to complete this project were a high proficiency in 3D CAD modeling, a knowledge of 3D printing in order to design the parts in a way that they could be 3D printed, and some control systems.

• Explain how you acquired or improved the skills needed for the completion the project.

I acquired these from the classes that I have taken. I built on these acquired skills through online resources and notes from the classes I have taken.

Form 4

To be completed by student
Assessment of Student Outcome # i

ME 4800

“A recognition of the need for, and ability to engage in life-long learning” is listed in ABET General Criterion 3. Student Outcomes as one of the student outcomes to be assessed for both Mechanical and Aerospace Engineering programs. As you work on your senior design project, we ask you to answer the following questions. These questions will help you to create the ideas needed to successfully complete your project and hence your ME4800 final report. You are required to submit the completed form in the last appendix of your final report.

Your responses will be used in the Evaluation of student outcome “A recognition of the need for, and ability to engage in life-long learning.”

A well-organized team brings together the necessary backgrounds and talents needed to successfully develop and complete the design process. Each team member plays an important role on the design team. Team members must be prepared to acquire any new additional skills, and improve existing ones during the development of the project. Your answers to the questions below will be used to evaluate a) your understanding of the need for life-long learning and b) your ability to recognize the need of acquiring new knowledge/skills when required.

ME 4800

Mechanical and Aerospace Engineering Design Project

For each team member:

NAME: Zachary Reinke

• List the skills you needed to execute your responsibilities on the project as outlined in ME 4790.

  The skills necessary for me to execute my responsibilities included CAD modeling, designing and programming system architecture for a microcontroller, building block diagrams in Simulink, implementing closed loop control using Simulink, data acquisition using a microcontroller, implementing sensors, and designing simple circuits.

• Explain how you acquired or improved the skills needed for the completion the project.

  I acquired and improved the skills I needed by taking the time early on in the project to study and experiment with the concepts that I needed to gain strength in. I did this by utilizing on-line resources, drawing on others experience, and spending the time necessary to learn by experience.