Wingtip Dynamics Simulator

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EXECUTIVE SUMMARY

Raytheon is a defense contracting company with an electronic warfare division that is developing a radio frequency signal triangulation system. Part of the focus in improving this technology is the need for accurate and real time locational knowledge of the signal receivers, which are located at the tips of aircraft wings. Due to turbulence during flight, the fluttering motion of the wings alter the distance and angle relationships of the two receivers and add noise to the received signal data, which negatively affect the triangulation estimates. To mitigate this error caused by the wing flutter, Raytheon is developing a software algorithm that predicts the precise locations of the signal receivers in space to attempt to clean up the incoming signal data.

As part of the development process at Raytheon, there is a need for a device that can move a signal antenna in random, flutter-like motion so rapid testing and refinement of the algorithm can be done. Thus Raytheon has made this project available for us to complete.

This project was completed over the course of one year, which was divided into three distinct phases of development. The first phase of the design process was research and design ideation. In this step, the project specifications that the completed device would have to meet was defined. Research into existing systems and available technologies was done to gain knowledge of the wide range of possible solutions that could be explored. During the second phase of the design process, various actuation methods and their feasibility for use in this project were analyzed, while iterative refinement of the device was also underway in parallel. The last phase involved building and testing the final design of the project.

The final product that was born out of this process is a two axis, large amplitude, low frequency shake device. The vertical axis is belt-driven with a servo drive and meets the required maximum motion of 11 inch stroke at 1.6 Hz. The horizontal axis is rack and pinion driven with a DC motor that is controlled by an Arduino board in closed loop control that met the maximum motion requirement of 1.1 inch stroke at 3.2 Hz. Both of the drive systems were capable of generating a pseudorandom motion that resembles the flutter of wingtips.

The rest of this report further details the research, analysis, design, manufacturing, and testing process that was performed to complete the project.

1. INTRODUCTION

The main goal of this project is to design and manufacture a testing device that will move an antenna in way that simulates a wingtip in flight in an anechoic chamber for the Raytheon Company.

Raytheon is a defense contractor that is divided into multiple divisions including Air and Missile defense, Cyber security, and Electronic Warfare (EW). Raytheon's EW division in Goleta, CA is developing and producing electronic warfare products such as radar warning receivers and jammers for the US military forces. These devices work through signal triangulation.

Triangulation is a method of measuring the distance and location of a signal emitter using at least two receivers mounted apart from each other, in this case an antenna on either wingtip of the aircraft. Each antenna receives a signal from the emitter, and based on the time variation of the signals, and the known location, velocity, and acceleration of the antennas, the system can detect where the emitter is located. This is useful in military applications and other scenarios to more accurately detect unseen threats and have greater situational awareness in the sky.

In order to properly implement this triangulation system though, one must account for the wingtip dynamics caused by wing flexure under flight conditions. Raytheon needs a test system designed and built that can simulate these dynamics. People who have an interest in our device, directly or indirectly, include Raytheon's software engineers and lab technicians and the aircraft pilots who will depend on accuracy of the signal triangulation system.

2. BACKGROUND

In the field of aeronautics, active knowledge of ground-based emitter locations is vital to the survival and mission success of tactical aircrafts [1]. Where the emitter towers work by detecting wave reflections off of the target, the passive emitter geolocation systems work by listening for delays in received waves and changes in wavelengths [2]. To locate a signal, multiple antennas are mounted on the aircraft wingtips. These points of reference provide data of the delay between receiving a signal on one detector to the other as depicted in figure 1. This is called the time-difference-of-arrival [3]. This data is combined with the known positions of the detectors to estimate the location of the ground-emitters [2].

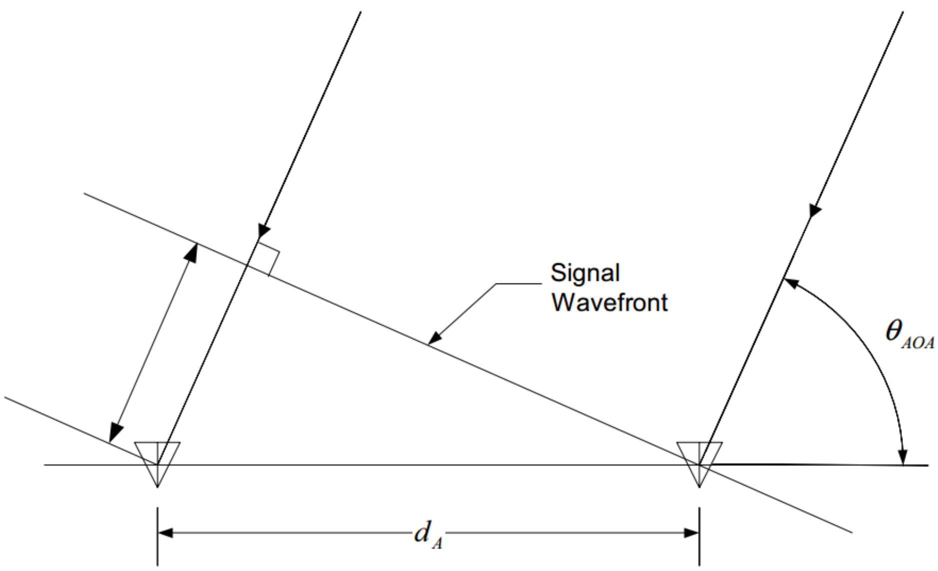


Figure 1: Diagram of emitter location estimation [6].

An obstacle in achieving high accuracies in such systems is the difficulty in knowing the precise location of antennas during flight [3]. The difference in lift generated along the length of the wing along with turbulence and wingtip vortices cause flutter in the wing. The flutter caused created during flight can vary the location of the wingtip antenna by as much as 11 inches in some crafts [5]. The flutter causes the wing to vibrate in an erratic sinusoidal pattern. One way to mitigate the effects of the flutter on signal triangulation is to employ software algorithms to predict the instantaneous location of the antennas [5]. This system combines the methods of triangulation, hyperbolic location, and statistics to produce accurate and combat ready triangulation implementation [4]. Thus to develop and calibrate this flutter-filtering software, a method of simulating the motion of a mounted antenna is needed.

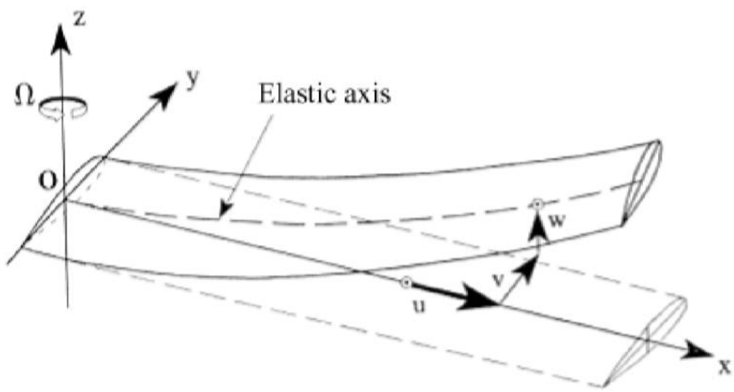


Figure 2: Wing deflection during flight [5].

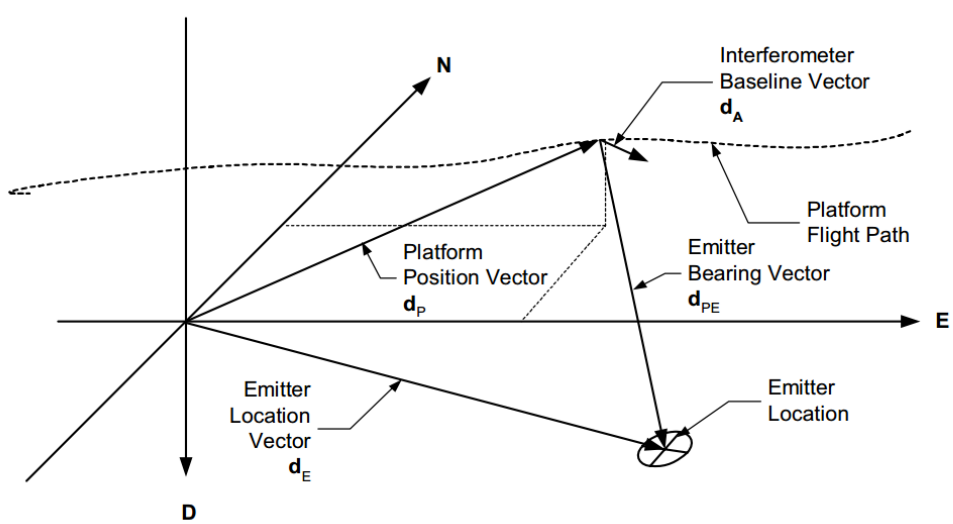


Figure 3: The varying path of antenna during flight [6].

2.1 Current Systems

2.1.1 Vibration tables

Vibration tables use mechanical means to excite a table surface at a high frequency. The research in currently available products led to the conclusion that most vibes tables only have max amplitudes in the order of .5inches, with high amplitude models barely accomplishing 3.5inches of displacement. 2-axis systems similar to what we need exist, but they also fall very short of our required 11” amplitude, with the largest found having 3” amplitude.

2.1.2 Industrial Vibration Platforms

There are two types of automobile simulation platforms; one type is essentially a scaled up vibration table and the other is a seismic simulation platform that uses electromagnetic and electro-hydraulic exciters. The large scale vibration table has the disadvantage of only being able to output one frequency and the amplitude adjustment is difficult. [11] Some automotive shakers that operate with electromagnetic and electro-hydraulic exciters could get the required motion profile. For both of these, however, the size is much larger than necessary and cost of the system is in upwards of hundreds of thousands of dollars [12].

Figure 4 : Indistrial vibration driver from Brüel & Kjær. [13]

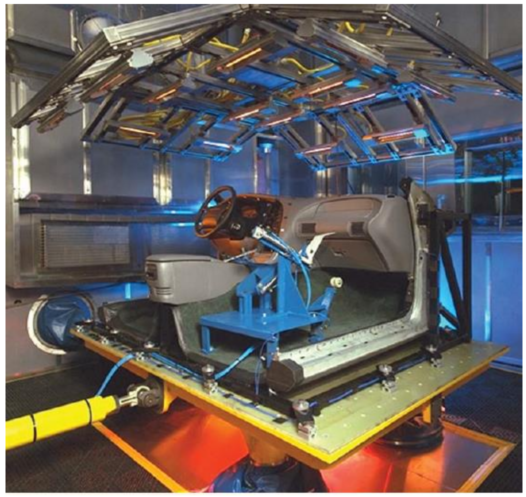


Figure 5: Instron Structural platform for use in automotive testing [7].

Table 1: Sample specifications for Instron Structural 6 axis motion platforms [7]

	Unit	MAST-9710	MAST-9720	MAST-9725	MAST-9730	MAST-9735
Pay Load used for Calculation	kg lb	300 660	450 990	450 990	800 2200	800 2200
Table Mass	kg lb	300 660	300 660	300 660	545 1200	545 1200
Table Work - Area Dimensions	mm in	1200 x 1200 47 x 47	1700 x 1500 67 x 60	1700 x 1500 67 x 60	2100 x 1800 83 x 71	2100 x 1800 83 x 71
Peak Acceleration - Vertical	m/sec^2 g	127 13	60 6.1	102 10.3	64 6.5	106 10.8
Peak Acceleration - Lateral	m/sec^2 g	100 10.1	48 4.8	77 7.8	50 5.1	80 8.1
Peak Acceleration - Longitudinal	m/sec^2 g	49 5	40 4	40 4	26 2.6	40 4
Peak Velocity - Vertical	m/sec in/sec	1.5 59	1.7 66	2.1 82	2 78	2 78
Peak Velocity - Lateral	m/sec in/sec	1.25 48	1.5 59	1.9 74	1.8 70	2 78
Peak Velocity - Longitudinal	m/sec in/sec	1 39	1.1 43	1.5 59	1.3 51	1.3 51
Stroke - Vertical*	mm in	±75 ±3	±75 ±3	±75 ±3	±75 ±3	±75 ±3
Stroke - Vertical*	mm in	N/A N/A	±125 ±5	±125 ±5	±125 ±5	±125 ±5
Stroke - Lateral	mm in	±75 ±3	±75 ±3	±75 ±3	±75 ±3	±75 ±3
Stroke - Longitudinal	mm in	±75 ±3	±75 ±3	±75 ±3	±75 ±3	±75 ±3
Operating Frequency Range	Hz	0 - 60	0 - 50	0 - 50	0 - 60	0 - 60

2.1.3 Large Motion Simulator

The only complete packages that exist that are close to meeting our requirements are large motion simulators like those used in high end flight and racing simulator games. These systems operate using a number of large amplitude actuators with inputs of real-time positions for each of the actuators to recreate the sensations of racing and flight. Although the actuators used in these products are less expensive than industrial grade electromagnetic actuators, they are still prohibitively expensive and they have the problem of the actuators not being able to move fast enough.

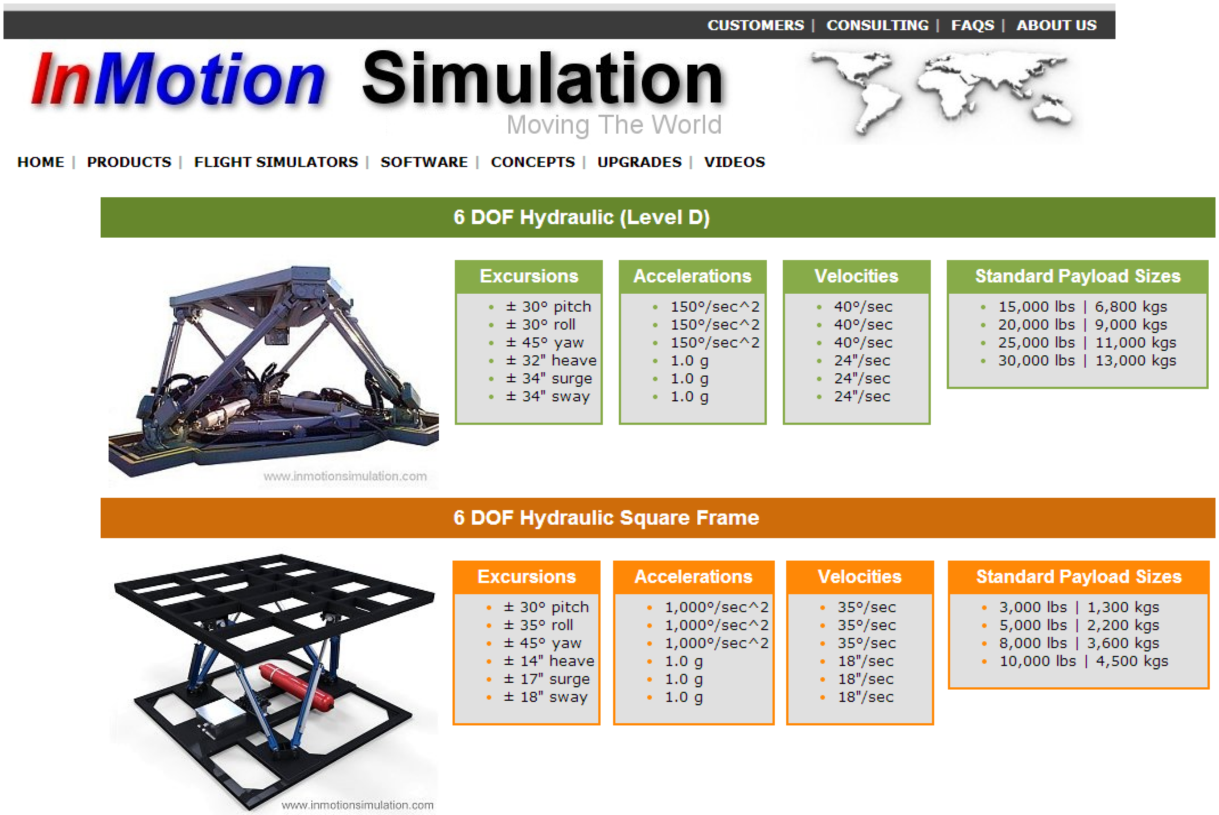


Figure 6: Flight simulator actuators [9].

2.1.4 Patents

Searching through the patents directory, we found conceptual ideas that have a possibility of being reconfigured to suit the needs of this project. A function that was focused on during the patent search was the creation of large amplitude vibration. A patent by the name of "Dual-frequency vibrating screen" [14] describes a system that pulls a fabric over a frame to create a tight sheet where objects can be placed and excited via external means to the frame. This patents points to a possibility of using a system of springs to amplify the motion from a smaller external excitation method. The patent, however, would only allow for a single direction of motion and would require a different system to incorporate a second direction of motion.

Another patent describes a design for a large scale vibration table to be used in aerospace and automotive testing [15]. This vibration table uses the principle of a cam and follower by driving a rod with non-circular cross-section below the table surface. The design claims to provide high carrying capacity, high frequency and overcome problems of longevity. However, the cam-follower mechanism would not provide an adequate amplitude for use in this project.

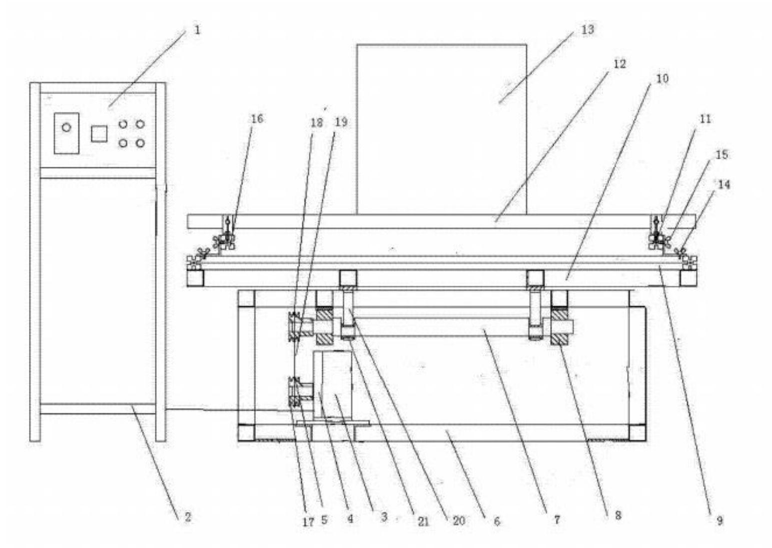


Figure 7: Patent drawing from CN203132810 U.

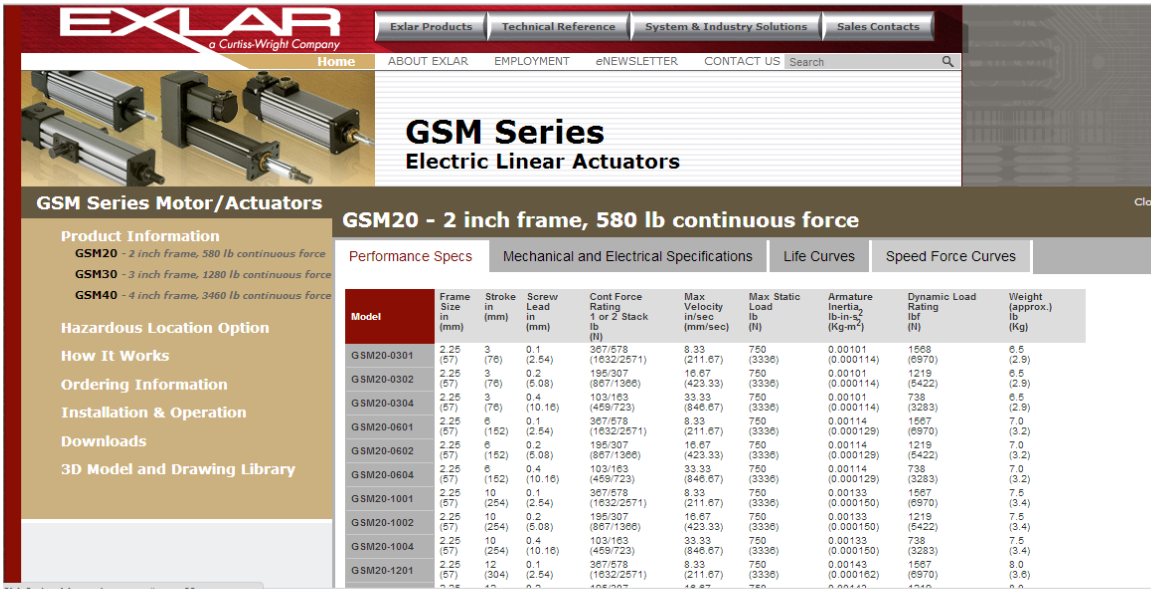
2.2 Methods of Actuation

2.2.1 Linear Actuators

Three common types of actuators are hydraulic, pneumatic, and mechanical. Hydraulic actuators have two chambers and a pump that pumps pressurized hydraulic fluid between the two to move a piston. Pneumatic actuators are similar but use pressurized air rather than fluid. This creates the need for an air compressor instead of a fluid reservoir. There are various types of mechanical actuators including those operating with a screw, wheel and axle (belt, chain, etc), or cam.

To start, the only actuators that can supply a reciprocating motion, rather than just pulling or pushing, are hydraulic, pneumatic, or lead screws. The most viable of these three options is the screw actuator, in which an electric motor is connected to the screw and can turn its rotational motion into linear motion in either direction. This method is better than both hydraulic and pneumatic because there is no loud, bulky compressor and no fluid reservoir, pumps, and lines running throughout the device.

Most linear actuators are either high frequency and low stroke, or high stroke and low speed. A few suppliers, including Exlar and Parker, were found that produced high amplitude linear actuators that were also high speed. These products had speeds of up to 2 m/s with a large enough stroke along with linear feedback which is needed for our controller.



Model	Frame Size in (mm)	Stroke in (mm)	Screw Lead in (mm)	Cont Force Rating 1 or 2 Stack lb (N)	Max Velocity in/sec (mm/sec)	Max Static Load lb (N)	Armature Inertia, lb-in-s² (Kg-m²)	Dynamic Load Rating lbf (N)	Weight (approx.) lb (Kg)
GSM20-0301	2.25 (57)	3 (76)	0.1 (2.54)	367/578 (1632/2571)	8.33 (211.67)	750 (3336)	0.00101 (0.000114)	1568 (6970)	6.5 (2.9)
GSM20-0302	2.25 (57)	3 (76)	0.2 (5.08)	195/307 (867/1366)	16.67 (423.33)	750 (3336)	0.00101 (0.000114)	1219 (5422)	6.5 (2.9)
GSM20-0304	2.25 (57)	3 (76)	0.4 (10.16)	103/163 (459/723)	33.33 (846.67)	750 (3336)	0.00101 (0.000114)	738 (3283)	6.5 (2.9)
GSM20-0601	2.25 (57)	6 (152)	0.1 (2.54)	367/578 (1632/2571)	8.33 (211.67)	750 (3336)	0.00114 (0.000129)	1567 (6970)	7.0 (3.2)
GSM20-0602	2.25 (57)	6 (152)	0.2 (5.08)	195/307 (867/1366)	16.67 (423.33)	750 (3336)	0.00114 (0.000129)	1219 (5422)	7.0 (3.2)
GSM20-0604	2.25 (57)	6 (152)	0.4 (10.16)	103/163 (459/723)	33.33 (846.67)	750 (3336)	0.00114 (0.000129)	738 (3283)	7.0 (3.2)
GSM20-1001	2.25 (57)	10 (254)	0.1 (2.54)	367/578 (1632/2571)	8.33 (211.67)	750 (3336)	0.00133 (0.000150)	1567 (6970)	7.5 (3.4)
GSM20-1002	2.25 (57)	10 (254)	0.2 (5.08)	195/307 (867/1366)	16.67 (423.33)	750 (3336)	0.00133 (0.000150)	1219 (5422)	7.5 (3.4)
GSM20-1004	2.25 (57)	10 (254)	0.4 (10.16)	103/163 (459/723)	33.33 (846.67)	750 (3336)	0.00133 (0.000150)	738 (3283)	7.5 (3.4)
GSM20-1201	2.25 (57)	12 (304)	0.1 (2.54)	367/578 (1632/2571)	8.33 (211.67)	750 (3336)	0.00143 (0.000162)	1567 (6970)	8.0 (3.6)

Figure 8: Sample of Exlar specification sheet for high speed, high amplitude actuators [8]

2.2.2 Cam/Follower and Crank/Connecting Rod

A cam and follower uses the non-concentric shape of the cam to impart linear motion on a follower. However, a cam is only able to push and cannot pull back on the follower. Thus a spring is necessary on the follower in order to maintain contact. Crank and connecting rod mechanism uses the concentric motion of the crank and converts it into a linear motion using a follower that has one end constrained to one direction of motion. Crank and connecting rods are able to both push and pull. Both of these options are somewhat viable for this project because long stroke can be achieved with proper mechanism design and the frequency can be varied with the speed of the motor. However, it lacks variability of amplitude and would excite the system with the same amplitude on each cycle.

2.2.3 Spring-Mass System

A spring-mass system would be useful as an intermediary component in our device by bridging some of the shortcomings of the aforementioned actuation methods. A spring-mass system can be tuned to resonate at two desired frequencies and the base of the springs can be excited using one of the actuation methods outlined. For example, it is difficult to find an affordable electric actuator that has a large enough stroke and frequency, but a payload suspended by springs could be excited with a smaller, more affordable actuator.

From our research, no systems similar to what we desire currently exist. In addition, the motion they produced would be very dependent on the mass of the payload, so in order to prevent the need for re-tuning any time a new payload was being tested, we would need to add a ballast device to our system. That way we could add or subtract mass to maintain a constant total mass.

2.2.4 Linear Servos

Linear servo motors utilize a technology similar to a MagLev Train and are composed of an array of magnets with a matching electromagnetic slider that glides over the magnets. Linear servo motors can have its tracks scaled to any length by connecting more magnetic tracks together and they are commonly used in manufacturing automation where a long linear translation is required. Linear servo motors can move with very high velocity and acceleration. The output force is less than linear actuators, but it is still sufficient for our use. The initial design plan was to use a linear servo in the system to drive both axis of motion because of the easily achievable high speed and acceleration and the positional control it offered, but later discovered that linear servo motors need high-voltage drivers and expensive encoders for it to work. The estimated cost for such a system was around $12,000.

2.2.5 General Purpose Motors

General purpose motors are inexpensive motors made with permanent magnets most commonly used for driving fans or pumps. They are intended to run at a steady rate for an extended period of time and take longer to ramp up to speed than a servo motor. Like the servo motor, an encoder can be mounted to give positional feedback, however they are not designed for high speed and high temperature use. Because of the slow acceleration and low heat dissipation, general purpose motors are not suitable for our use.

Figure 9. 12V DC Motor [16]

2.2.6 Servo Motors

Servo motors are motors that allow for angular position control using either a built-in encoder or a retrofitted encoder. Most servos are designed to have a high input voltage and good thermal dissipation in order to deliver high acceleration and continuous motion. A specialized servo drive must be used in order to supply adequate voltage and control to the servo. Servo motors are more expensive than the general purpose motors, but have the capability to deliver the performance needed at a lower cost than most linear actuators.

Figure 10. TLY-Series Servo Motor [17]

2.3 Drivers

Motors drivers, also known as amplifiers or speed controllers, power the motor and enable it to perform to the desired specifications. Servo motors are driven by specialized servo drivers which are electronic amplifiers that amplify a command from the controller and give a varying output to the motor to match the desired motion. These servo drivers can output the command signal in terms of desired velocity, position, or torque, depending on the requirements. General purpose motors are driven by speed controllers that power the motor using pulse width modulation. PWM is when the controller sends on and off signals in rapid succession to the motor so it appears that the motor is only operating at a fraction of its total power. This is needed because the motor can't normally operate at variable power, only fully on or off.

2.4 Controller

Programmable logic controllers (PLCs) can be programmed with a desired motion. They receive inputs from a sensor on the system and give an output to the motor. For our system, a microcontroller can receive digital inputs from a position, velocity, or acceleration sensor and output a PWM signal to our driver. Arduino makes a Uno microcontroller which is a microcontroller on a circuit board. Arduino microcontrollers are inexpensive, easy to use, and flexible to be customized.

Figure 11. Arduino UNO Microcontroller [18]

2.5 Anechoic Chamber

An anechoic chamber is a shielded enclosure coated in absorption material that prevents any external or internal radio frequency signals from interfering with emission measurements. It is used to increase accuracy and repeatability of testing antenna radiation patterns, electromagnetic compatibility, and radar cross section measurements. RF absorbing material (RAM) is used to reduce reflections of incident RF radiation from as many directions as possible, for this reason its most effective setup consists of an array of pyramid shaped pieces that cover the entire room. Any testing devices that have exposed metal must also be coated in this RAM to prevent reflection of RF. The standards for certification of anechoic chambers and RAM are found in the Department of Defense Interface Standard 461E. It states, "During testing, the ambient electromagnetic level measured with the EUT de-energized and all auxiliary equipment turned on shall be at least 6 dB below the allowable specified limits when the tests are performed in a shielded enclosure." [10]

To ensure our testing device doesn't reflect RF above the allowable limit, we will cover any exposed metal with RAM. This may require larger portions of RAM if any moving parts on the device would expose themselves during testing. There is an anechoic chamber on Cal Poly's campus that we will be able to use for verification of our device's RF "quietness." One issue we may run into due to this insulation is the reduction of heat transfer from our testing device. If most of the device is covered by RAM, it will be highly insulated and we may need to integrate a cooling system depending on how much heat the device generates.

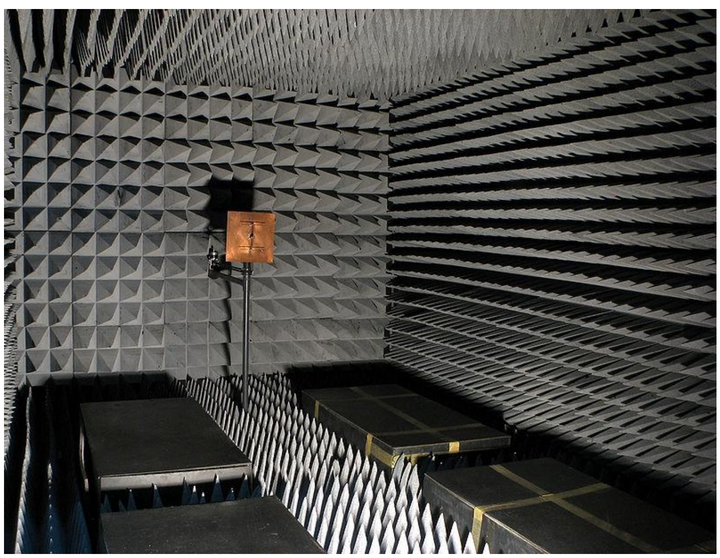


Figure 12. Anechoic Chamber [19]

2.6 Data Acquisition

For some of the systems we have been looking into, either the actuator or the motor supply positional feedback. For systems in which neither of these components have sensors, we will need to incorporate a sensor to either measure position, velocity, or acceleration. The easiest of these to measure is position through the use of linear encoders or potentiometers. Our servo motor is paired with an incremental encoder that gives position feedback to the driver. And on both axes, we will put linear magnetic encoders to give accurate position data about the test sensor.

2.7 Power Sources

The components in our system that need to be powered include the motor, driver, microcontroller, and encoder or potentiometer. As stated earlier, each motor will be powered by its respective driver or speed controller. The driver we have chosen for the vertical axis, the Allen-Bradley Kinetix 3 drive requires 1 phase, 240 VAC input which can be obtained from 240V wall sockets. Standard microcontrollers need 5V input and can be powered by a USB cable, AC-to-DC adapter, or a battery. Finally, various magnetic linear encoders we have been looking into are powered through a control cable that will be connected to our computer.

Figure 13. Kinetix 3 Servo Drive [20]

3. OBJECTIVES

Raytheon develops antennas to be mounted on the wingtips of planes used for radar triangulation systems, which transmit important information to the pilots. The flutter motion of the wingtips in flight decreases the accuracy of the triangulation system, and it is important to be able to predict the location of the wingtip under flight conditions to more accurately implement signal triangulation. Software solutions exist that filter out the noise and correct for antenna location, but they must be tested, preferably on the ground and not in flight. A portable system to simulate flight conditions is needed and must fit in an anechoic chamber at the Raytheon facility. The objective of the project is to create a two-axis, low frequency, high amplitude vibration device that simulates the motion of an antenna during flight and transmits real time data of antenna position, velocity, and acceleration.

3.1 Customer Requirements

The customer requirements shown below were provided by Raytheon and are the basis for our engineering specifications we developed.

Table 2: Customer Requirements

Requirement	Comments
Simulate flight conditions of wingtip	Motion needs to match the supplied profiles as closely as possible
2 Axis System	Needs to move the antenna in the vertical and horizontal axis
Selectable motion and frequency	4 specific motion profiles need to be able to be produced
Random Amplitude and phase inputs added	System needs to be able to simulate random impulses that will significantly change the motion of the system to simulate turbulence and other fluctuations in the wingtip
Real-time knowledge of motion	System must output position, velocity, and acceleration data in real time
Test system does not reflect RF	Metal surfaces would reflect RF, altering the signals detected by receiver
Reusable test machine	Device needs to be durable, and capable of being used for many tests
Mount payload on device	Must support a variety of payloads. Can't be made custom for each one
Can be transported to Raytheon facility	
Must be a reasonable price	
Quick setup time and turn around rate	

3.2 Formal Engineering Requirements

The Formal Engineering Requirements we are proposing are listed below. We used Quality Function Deployment (QFD) to interpret all customer requirements and identify the engineering specifications. The House of Quality can be found in Appendix B.

Table 3: Formal Engineering Requirements

Spec. # Parameter	Description	Requirement or Target	Tolerance	Risk	Compliance
1	Multi axis movement	2 axis of motion	Min	M	S, I
2	Can accelerate load in x and y axis	.6g in x, 1.4 in y	Min	M	A, T
3	Can produce 4 specific motion profiles	4 profiles	Min	L	A, I
4	Data refresh rate is 4-10 times bandwidth	30Hz	Min	L	T, I
5	Impulses can be added that will extend vertical displacement	11in displacement	Min	H	A, T, I
6	No RF Reflection	Sensor only receives signals from transmitter	Max	L	A, I
7	High expected lifetime	10000 cycles	Min	L	A, S
8	Can fit through door	3ft*7ft	Max	M	I
9	Accuracy	±5%	Max	L	A, S
10	Accommodates payload	10lbs, 6in diameter	Min	L	I
11	Cost	$5,000	Max	M	A, S
12	Multiple independent tests per day	3 tests	Min	L	T
13	Impulses can be added that will extend horizontal displacement	1.1"	Min	H	A, T, I
14	Clarity of instructions	Able to fully operate system after 1 hour reading instructions	Max	M	T
15	Time to set up device	3 hours	Max	M	T

On the list of Formal Engineering Requirements, the Tolerance states whether each requirement or target is the maximum or minimum value needed for compliance. The Risk column lists the difficulty we expect to experience in meeting the goal. We expect to face the most difficulties in producing high enough accelerations and displacements for our device. Compliance shows the methods by which we will ensure each requirement is met. These procedures include Analysis (A), Test (T), Similarity to Existing Designs (S), and Inspection (I).

Requirements 2, 5, and 11 will be tested by looking at the motion profile output by the onboard sensors and verifying that it matches the required output. Requirements 14 and 15 will be verified by recruiting volunteers to attempt to learn and use the product once it is complete.

A short explanation of each specification is provided below:

1. The motion of the wingtip can be approximated as 2 axis motion, so the system must replicate this.
2. These accelerations were calculated from the motion profiles supplied by Raytheon.
3. The wing vibration model shall contain 2 modes in each axis:
    - Vertical:
        - 1.6 Hz, 6.6 cm (zero to peak) sinusoidal with nominal guests, 1σ.
        - 3.2 Hz, 1.7 cm (zero to peak) sinusoidal with nominal guests, 1σ.
    - Horizontal:
        - 3.2 Hz with amplitudes 10% of vertical.
        - 6.4 Hz with amplitudes 10% of vertical.
4. The definition of real time as supplied to us by our sponsor is 4-10 times the bandwidth of operation, which in our case maxes out at 6.4Hz.
5. The device must have displacement limits of ±11in in the vertical direction. These displacements are achieved by adding pseudo-random impulses to the primary modes of vibration.
6. RF reflection by our device could compromise the test.
7. All components will be designed with maximum lifetime in mind.
8. Must be able to get in and out of buildings with standard doors, either complete or disassembled.
9. Data output must be within ±5% of actual.

10. Must be able to accommodate the supplied payload. Mounting hardpoints must be flexible enough for a variety of payloads.
11. Budget expected to be $3000-$5000.
12. Same as specification 5, only in the horizontal direction with a smaller amplitude.
13. Setting up and resetting the test can't take an excessive amount of time.
14. System must not require special training to use, or be too complicated to use effectively without extensive practice.
15. Initial set up must be relatively quick, as lab space is valuable. Less time setting up means more time doing useful work.

4. DESIGN DEVELOPMENT

4.1 Ideation

After sufficient background research was done so that we felt that we understood the project scope, we began a series of idea generation exercises. To assist in staying focused for ideation, four main functional area were identified as important to the project. The four functions were "generation of motion", "random noise input", "2D constrained plane of motion" and "data acquisition." For each of these functional areas, we performed brainwriting as the first exercise. Brainwriting involves writing down as many ideas as possible on a sheet of paper in a short timespan (no more than 5 minutes) then switching the sheet with other team members to perform another round of brainwriting. The second exercise was a series of brainstorming sessions using sticky notes to rapidly create and branch off ideas. Lastly, we created some models of our ideas using foam core, legos, office supplies, and other craft material to quickly verify viability of ideas and demonstrate functions. In the end, we generated 87 distinct ideas that could potentially be useful in solving our problem.

4.2 Evaluation

After generating an extensive list of all possible ideas for our four functions, we began to evaluate them. Our first process was Go No-Go in which we eliminated all the unreasonable ideas generated through ideation. This included ideas that were simply far too expensive or technically impossible. The Go No-Go cut down our ideas almost in half.

We followed this with our first set of Pugh matrices in which we chose our best concept to set as the datum and compared it to all other concepts for a variety criteria for each function. This allowed us to determine if there were some ideas which at first looked inferior to our datum, but actually were superior in certain aspects. It also allowed us to see those ideas that were inferior to the datum in every quality so we could eliminate them easily.

The second set of Pugh matrices consisted of all the top concepts from the previous matrix gathered into sets of systems. We evaluated a variety of these systems under more specific criteria including quickest response time of payload and ease to vary the amplitude of the payload motion. We were left with three final systems that stood out: a direct mechanical actuator, a cam and spring combination, and an actuator with a spring. These ideas were chosen for their combined superiority in price, complexity, configurability, and how well they produced the desired motion.

Finally, we had to weight each criteria so the systems that were superior in the most important aspects would stand out. To create this weighted decision matrix, first we had to figure out an accurate weight for each criteria. We calculated the various weights through use of pairwise comparison. The criteria were individually compared to each other and the more important criteria got a point for each comparison. The ratio of points for each criteria to the total points generated gave us the weight. We used this weight combined with how well we were satisfied with each concept's performance to calculate a weighted score for each criteria and, summing the scores up, could pick the best concept. The mechanical actuator was chosen as our top concept followed by the spring-actuator combination. Although further research into actuator price could prove that long stroke mechanical actuators are out of our budget in which case we will proceed with the spring driven system. Please see all Pugh matrices and the weighted decision matrix in Appendix C along with explanations for each criteria and justifications for the scores.

4.3 Top Concepts

4.3.1 Spring Drive

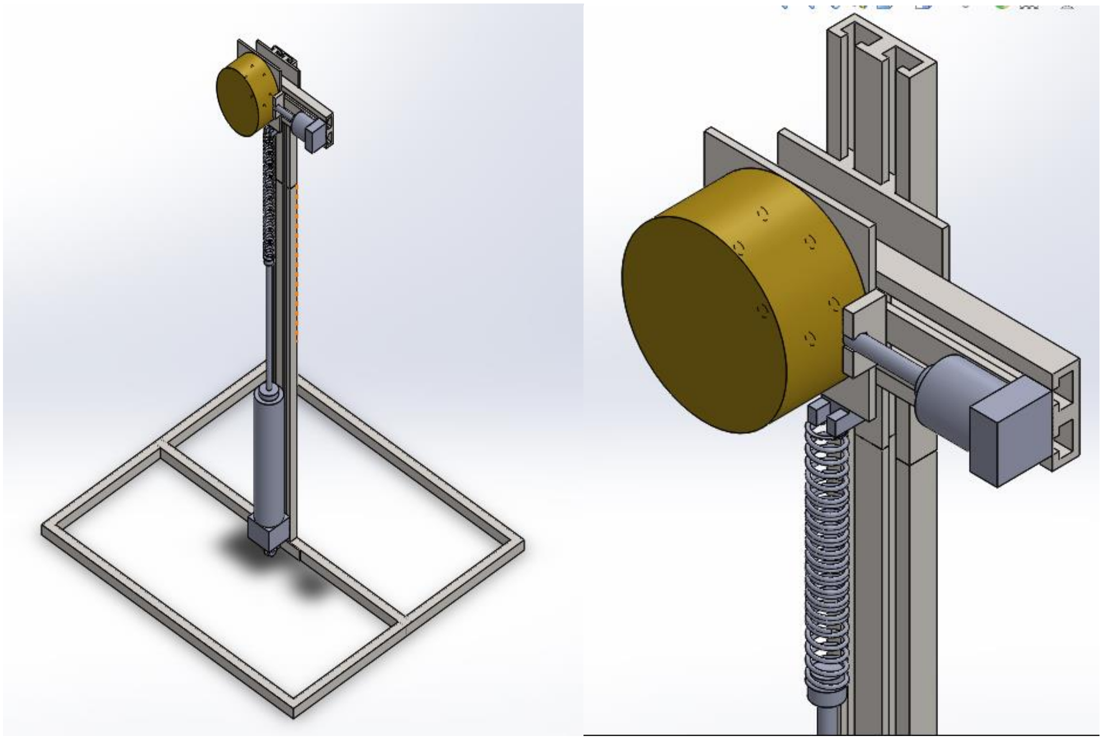


Figure 14. Draft 3D model of spring-actuator design.

This system will be driven by a short stroke mechanical actuator in the horizontal axis and a medium stroke actuator combined with a spring in the vertical axis. The payload will be attached to a carriage that slides along a rail in the horizontal axis. This rail will also be attached to a carriage that will slide along a vertical rail. The payload carriage will be connected directly to a small linear actuator, which will be controlled via a servo controller. This will allow amplitude and frequency of motion in the horizontal axis to be input directly with complete control.

The vertical axis will be driven by an actuator connected to the carriage by a long spring. This spring will amplify the motion of the actuator, and allow for the high speeds and displacements needed by the system. This actuator will also be controlled by a servo controller, but the inputs will need to be generated beforehand to guarantee the output motion matches the desired profile.

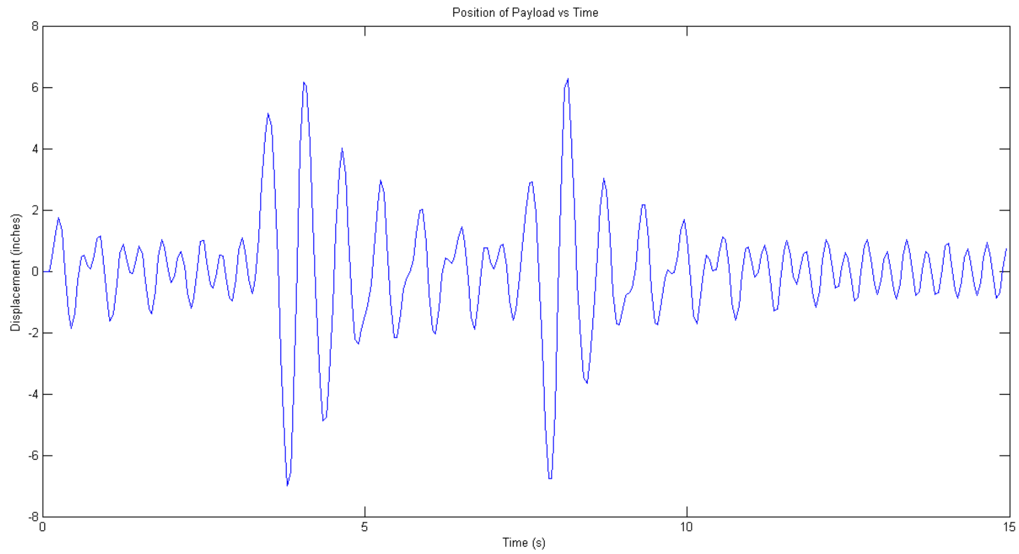


Figure 15. Proof of concept Matlab simulation of payload movement due to base excitation.

Motion profiles can be generated in advance for each actuator to allow the system to operate at each of the 4 primary frequencies. The spring in the vertical axis may need to be swapped for one of a different stiffness when the vertical frequency changes.

In order to conduct initial testing on the system, the rail and carriage for the vertical axis would need to be purchased, as well as the actuator and spring. A compatible servo controller for the actuator will need to be determined and purchased as well. A dummy weight will need to be mounted to the carriage, and the spring and actuator attached to the carriage. Testing of the spring-actuator system can then begin, with coding for the control of the actuator beginning and being tested on the real system to verify it works properly.

Once the system has been shown to work in one axis, parts for the other can be ordered and final assembly can be completed. From there, testing of the full system with motion in both axis will begin.

4.3.2 Direct Drive

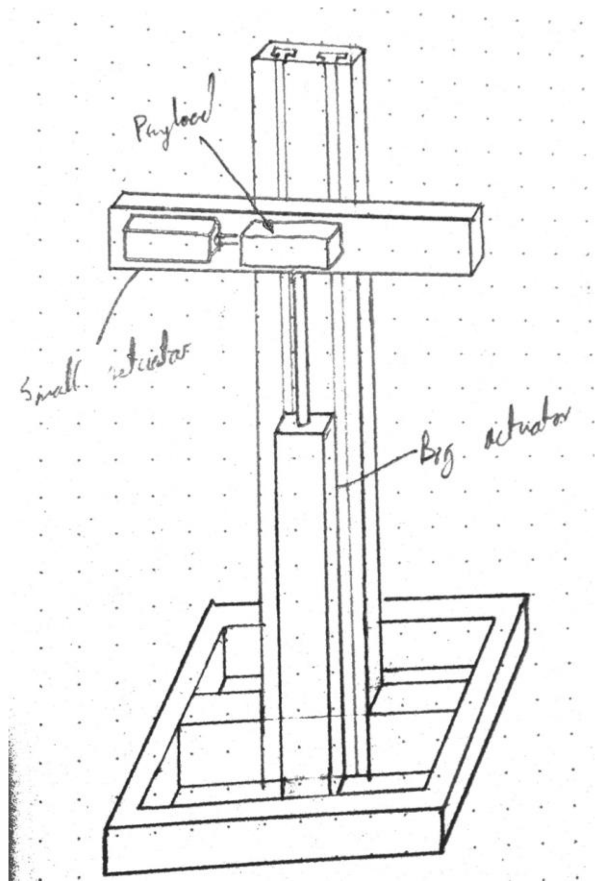


Figure 16. Sketch of direct driven payload.

This system will be identical to the previous system except for the vertical axis will no longer have a spring in it. This concept requires a sufficient budget to purchase an actuator with a long enough stroke and high enough speed to not need spring amplification. This would allow for the vertical axis to be directly controlled just like the horizontal axis, meaning generation of movement profiles would be much easier and faster, as well as more flexible in the kinds of motion it could generate.

4.3.3 Outcome of Top Concept

At the end of the Concept Design Review, we were excited that we had found a seemingly feasible drive mechanism and design to meet our project goal. On the surface, mechanical actuators seemed like they would be within the budget. However, when we began delving deeper into actuator suppliers, we discovered that linear actuators require a separate purchase of a high powered servo motor and an equally expensive servo drive. The problem was that there are no vendors who supply inexpensive hobby-grade linear actuators with the required speed and stroke and actuators intended for heavy factory-use were grossly overpowered for our need. Once we learned that going with a pre-built linear actuator was not feasible, we decided to construct our own actuator mechanism using a servo motor. The resulting design is outlined in the following sections.

5. FINAL DESIGN

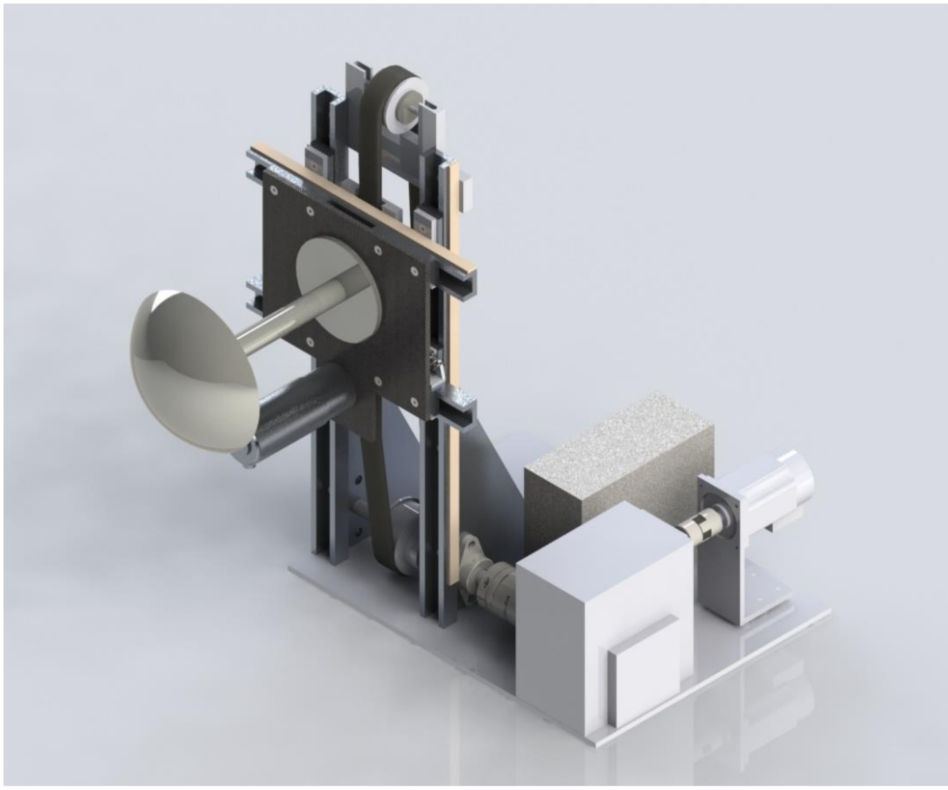


Figure 17. Overview of final system design.

5.1 Description of Product and Features

The final design for the wingtip dynamics simulator is shown above. The main driving mechanism of the system is a servo motor and belt drive for the vertical motion and a DC motor on a rack and pinion for the horizontal motion. The two axes of motion for the payload will be independently controlled and a linear encoder will collect data on the location of the payload during the test. To simplify the operation and function of each distinct subsystem, the description of various component groups will be divided up in five sections: vertical electrical subsystem, vertical mechanical subsystem, horizontal electrical subsystem, horizontal mechanical subsystem and the frames, rails and base.

5.1.1 Vertical Electrical Subsystem

The main component of the vertical motion is the Rockwell Automation's TLY-230 series servo motor. This servo offers sufficient power needed to simulate the motion of a wing tip. It has efficient thermal dissipation, which allows the servo to be continuously run through rigorous motion routines. The servo motor is driven by a matched servo drive from Rockwell Automation called the Kinetix 3 and offers control of the servo motor using feedback from an encoder. An encoder is attached on the vertical rail, which will allow for data collection on the position with accuracy of up to 0.001in. The user interface and motion profiles will be programmed using the RSLogix software.

5.1.2 Vertical Mechanical Subsystem

Since the motor has a high optimal operation speed (4500 RPM), a 20:1 gearbox will step down the speed and at the same time increase the torque. A favorable side effect of using a worm gear based gearbox is that upon system shutdown, the worm gears will self-lock and the payload will not crash down. The rotational motion from the gearbox will be transferred into a belt drive, which will create the long stroke vertical motion. The vertical stroke will be transferred onto a carriage mounted on two rails.

5.1.3 Horizontal Electrical Subsystem

The electrical system includes a DC motor and a DC speed controller. The DC motor will be receiving an input signal from a microcontroller like the Ardruino microcontroller board. The signal input will be a sine wave with varying amplitudes and frequencies. The speed controller then translates the signal into a larger voltage PWM signal to move the motor at a certain power. As with the vertical orientation, there is an encoder mounted on the rails for positional knowledge.

5.1.4 Horizontal Mechanical Subsystem

Much like the vertical orientation, the horizontal motion is constrained by use of two parallel rails. The motor at the bottom of the payload platform is connected to a pinion gear. A rack gear is connected to the rails, which slide independently from the payload platform, and allows for an oscillating horizontal motion. Since the DC motor with the DC speed controller will not offer any kind of feedback, a spring system will be mounted to force the horizontal system to stay centered while the device is operating.

5.1.5 Frames, Rails and Base

There are two sets of rails (two in the vertical direction and two in the horizontal) that act as a motion constraint for the payload support for the whole device. The rails fit with carriages that were selected and mitigate the moments the belt would not be able to support. The base is a simple rectangular plate of aluminum with matching bolt holes for all the components. At the top of the belt drive system is an intuitive belt tensioning system; the two bolts below the free spinning shafts can be screwed in to raise the free pulley higher and increase tension in the belt.

5.2 Manufacturing Process

The majority of the parts being used in this design come either in their final form or very close to it. The rails, angle bracket, and bottom plate will have their major features roughed out with a band saw, then a finishing pass taken with a mill where necessary. Holes will be located by hand and then drilled on a drill press. The drive shaft and free pulley axle will both be cut from a longer rod on a band saw.

For more detail on any part which has a manufacturing process more complicated than those above will be found in Appendix H, on the page following it's detailed design drawing.

5.3 Integration Concerns

An area of concern regarding timely completion of the build process is programming the driver for the servo motor. No one on the team has much experience in configuring motion control hardware except from Controls and Mechatronics class so we may face some challenge. However, there is a Rockwell Automation lab on campus where there is motion control equipment that is pre-configured and many commonly used hardware programming languages that are available for our use. Thus we feel that we have the capacity and resource to learn and create a routine for testing.

5.4 Design Analysis

See Appendix D for all calculations and part specifications.

5.4.1 Motion Requirements

Raytheon provided us with the amplitudes and frequencies of two modes of vibration for each axis. Using this data, we were able to calculate the maximum velocity and accelerations required for each axis. The payload must be able to accelerate at 1.4g and reach a max velocity of 55.3 in/sec in the vertical axis and accelerate at 0.6g to a max velocity of 11.0 in/sec in the horizontal axis.

5.4.2 Motor Sizing

From the payload weight and previously calculated motion requirements, we determined the maximum force and power that needs to be applied on each axis. Given a 10 lb max payload weight, we assumed the total weight in the vertical axis will be 15 lb. When the payload is at the bottom of its oscillation and is accelerating upwards, it needs to fight gravity and thus experiences an acceleration of 2.4g, resulting in 36.6 lb needed for the motion. These dynamics can be supplied by using a 0.31 HP motor. Assuming the total weight to be moved in the horizontal axis is 13 lb at an acceleration of 0.6g, 7.47 lb is required to move the mass accordingly. A 0.0125 HP motor can produce this motion. For the vertical axis, we ended up selecting a 0.59 HP servo motor from Allen-Bradley. The motor was selected due to its high thermal dissipation and ability to sustain continuous motion and high accelerations. When geared properly, the motor will be sufficient for our device. For the horizontal axis, we selected a geared, 12 V DC motor supplied by McMaster. It can generate 0.073 HP and doesn't need to be geared further to suit our purposes.

5.4.3 Drive and Controller Selection

Since the servo motor we are using for the vertical axis requires such a high input voltage and high control, it needs a specialized drive. The Kinetix 3 servo drive, also manufactured by Allen-Bradley is compatible with the motor we selected and can give us closed loop position control of the motor. It can supply 400 W, which is sufficient to power our 0.59 HP (or 440 W) motor, but is not capable of outputting power that will exceed the motor's rating. For the DC motor in the horizontal axis, we chose a motor driver from Pololu based on its voltage and amperage specifications. It can deliver 12 A continuously (5.91 A are required by the motor), and it operates from 5.5V-24V so it can drive our 12V motor.

5.4.4 Rack and Pinion Sizing

To actuate the horizontal motion, our design will use a DC motor mounted to a rack and pinion system. In order to minimize chances of burnout, it is more desirable to operate the motor near its rated max speed. Therefore, the diameter of the pinion must be determined that will generate the required maximum speed on the rack. Given the DC motor speed of 179 RPM and the maximum horizontal velocity of 11.1in/s, the necessary pinion size was determined to be at least 0.587in. A pinion size of less than the derived value would fail to achieve the required velocity; therefore when looking for the part, a pinion of size equal or greater must be chosen. Steel gears will be chosen and the gear stresses are assumed within safe ranges since other more demanding gear analysis has yielded huge factors of safety and also since the horizontal axis experiences loads far less than the vertical. The rack will be selected to match the teeth specifications of the chosen pinion.

5.4.5 Gearbox Selection

To step down the servo motor speed and increase torque, a gearbox offered the best option for a preconfigured package that would be simpler to install than a full gear train constructed by us. Knowing that the servo motor will need to be driven at a maximum of 0.31hp and that the optimal power output occurs at 5000 RPM, a 20:1 gearbox from McMaster Carr was selected. Its maximum input power specification is 0.52hp and maximum input speed of 4500 RPM. At 4500 RPM, in conjunction with the selected driving pulley size, the gear ratio of 20:1 will create the speed and torque we need on the belt. In addition, the input speed restriction on the gearbox would mean that the servo motor has to speed up to 4500 RPM rather than to 5000RPM and be quicker to reach necessary speeds.

5.4.6 Gear Bending Stress

To ensure the selected gears do not fail under the expected loads they will be subjected to, we compared the yield strength for 1018 steel with the bending stress experienced by the drive pulley in the vertical drive system. We used Shigley's Mechanical Engineering Design, 9th edition for all necessary factors and material specifications. From the analysis, we concluded that the gear has a factor of safety of 19 against bending stress. We did not perform any stress analysis on the rack and pinion set up for the horizontal axis due to the extremely large factors of safety present in the vertical axis.

5.4.7 Carriage Loads

As the payload moves up and down, the cantilevered payload imparts a moment on the four carriages on the rails. Carriages are rated for a maximum dynamic load of 336lbs and the maximum load experienced on a carriage is 57.8lbs giving a safety factor of 5.8.

5.4.8 Vertical Rail Deflection

As the payload moves horizontally, the vertical rails experience a side to side twisting moment, which may cause a deflection in the rails. However, the analysis for bending showed that the effect is negligible since the loads are minimal.

5.4.9 10-32 Bolt Pullout

At the base of the vertical rails, the horizontal motion of the payload applies a moment and a pulling force onto the bolts. The vertical tension force on each of the bottom plate bolts is 23.4lbs. Since the bolts are made of steel and the angle supports are made of aluminum, the angle brackets are the higher risk of the two. The internal thread has a thread engagement area of 1.5152in^2 where the 23.4lbs of force creates a stress of 15.44psi. Aluminum's ultimate tensil strength is 45000psi; therefore, there is no risk of bolt pullout.

5.4.10 Spring Selection

Since the damping coefficient of the rails is unknown and not published, we will wait until we have the parts in hand to conduct tests to determine the damping coefficient. Once the coefficient is known, we can determine the spring constant required for the horizontal axis drive system.

6. PRODUCT REALIZATION

6.1 Manufacturing Process

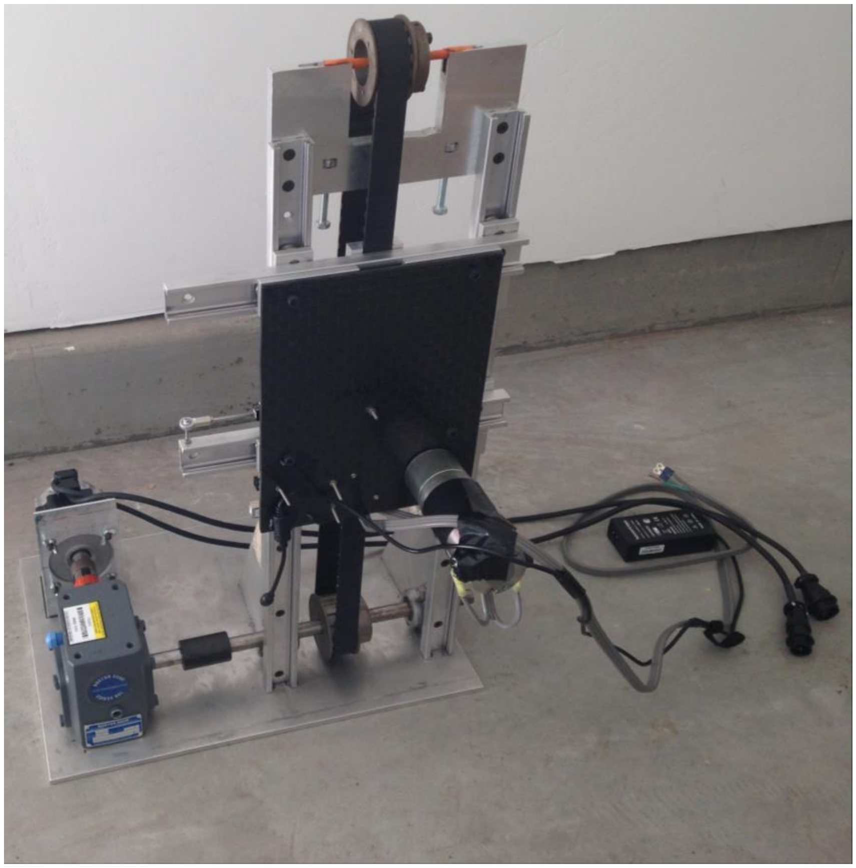


Figure 18. The final product.

This project involved a tight integration of both hardware and electronics, thus the manufacturing of the mechanics and development of the electronic drive systems occurred in parallel. This section outlines the process and outcome of the build phase and is divided into sections according to the functional subassemblies.

6.1.1 Structural Hardware

Figure 19. (Left) The angle brackets with bearings installed and drive shaft attached to the gearbox. (Right) Rail and carriage assembly attached to angle brackets and gearbox.

Both angle brackets were cut from a single large rectangular plate of aluminum on a band saw, and then holes were drilled and tapped in the two perpendicular sides to allow the rails and base plate to be attached. Mounting holes for the vertical drive shaft bearings were drilled in each bracket, as well as a larger hole for the drive shaft to pass through.

Carriages were mounted to their corresponding rails via pre-drilled mounting holes after the rails were cut to length.

6.1.2 Payload Plate

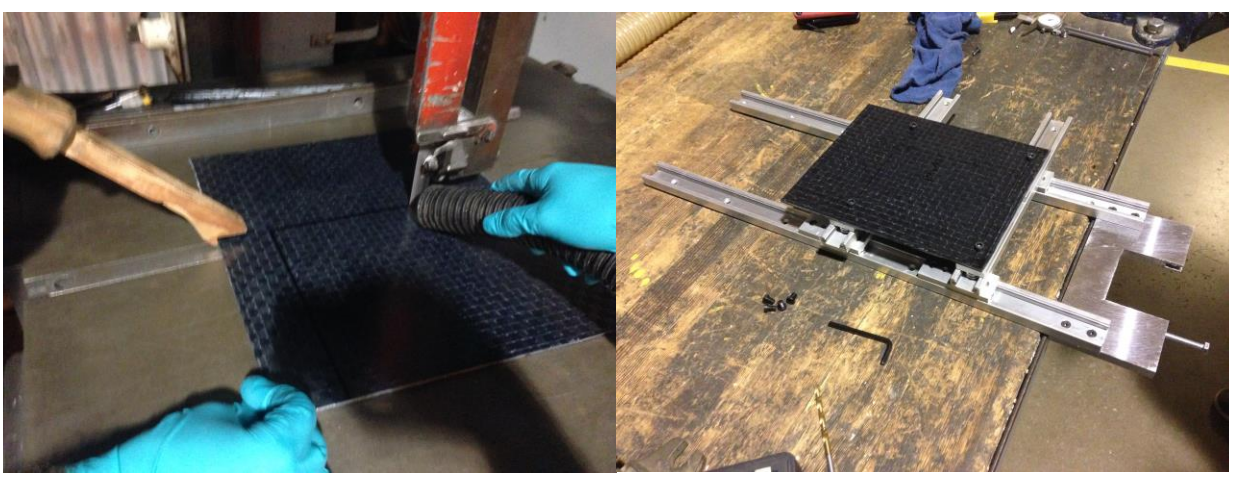


Figure 20. (Left) Payload plate being cut on a band saw. (Right) Payload plate attached to rail and carriage assembly.

The payload plate was cut from carbon fiber on a band saw, taking care to vacuum away excess carbon dust. Mount holes were then drilled and the plate was bolted to the four carriages that slide in the pair of horizontal rails. These rails were then bolted to the four carriages that slide in the pair of vertical rails.

6.1.3 Vertical Drive System

Figure 21. (Left) Belt clip being made on a mill. (Right) Belt clip attached to belt and rail.

The belt clip was milled out to have 3 grooves corresponding in size and spacing to the ridges on the drive belt. Then two holes were drilled and tapped on either side of the grooves to allow the clip to be bolted onto the upper horizontal rail.

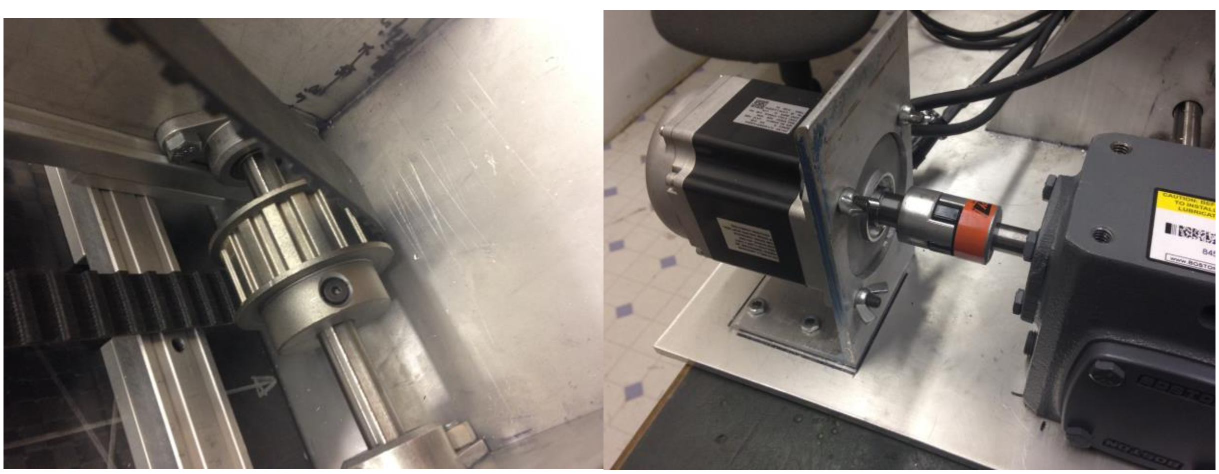


Figure 22. (Left) Drive pulley attached to drive shaft with belt in place. (Right) Vertical drive motor mounted to the base plate and connected to the gearbox.

The drive pulley was mounted onto the drive shaft in between the two angle brackets using a set screw which fit into the keyway in the drive shaft.

The vertical drive motor was mounted onto an aluminum angle bracket via four bolts, and that bracket was in turn bolted to the base plate. The large circle in the motor bracket was machined out using a mill while being held on a rotary table so the very large diameter circle could be cut evenly.

The gearbox was bolted down to base plate by drilling holes in the base plate matching the pattern of holes that came preinstalled in the gearbox housing.

6.1.4 Horizontal Drive System

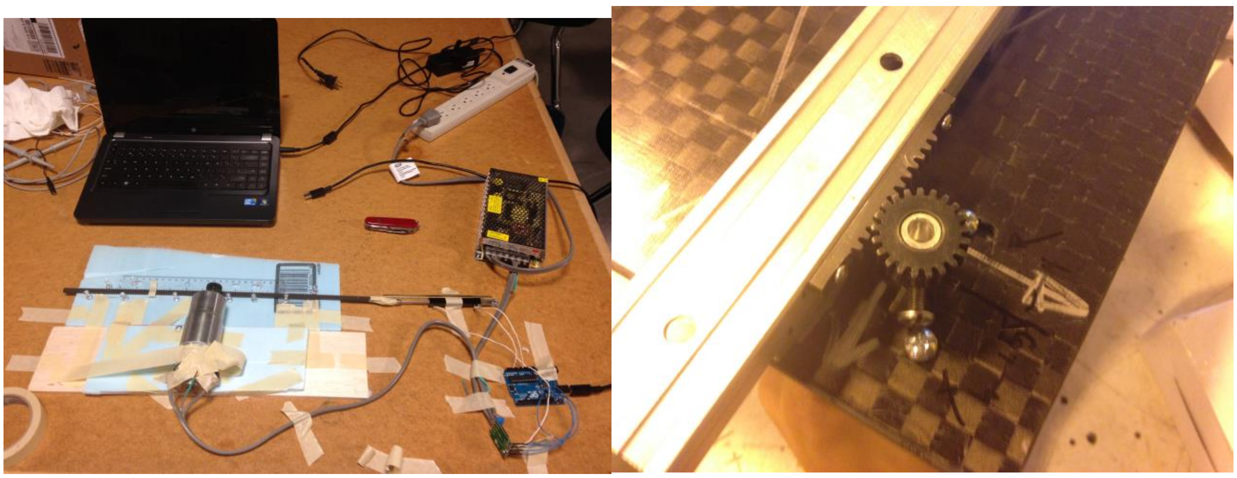


Figure 23. (Left) Horizontal drive motor and electronics being tested. Tape was used to allow breakaway in case of overextension. (Right) Horizontal drive rack and pinion installed on the back of rail and payload plate.

The horizontal drive motor was mounted to the payload plate using the preinstalled mounting holes on the face of the motor. One of the holes in the payload plate was extended into a slot on the mill to allow the motor to be adjusted closer or further from the rail.

A potentiometer was mounted between the payload plate and the rail using small bolts to allow for positional feedback to the motor control system.

6.1.5 Vertical Electronics Development

Developing the vertical drive electronics required understanding the interactions between the high tech components and the necessary steps to power-up the drive electronics. Powering the Kinetix 300 servo drive and enabling it to power the motor was the most difficult part of this development process. The drive required 240 VAC single phase input power, which was only found in one outlet at the AERO Hanger. After building a plug and circuit breaker assembly in order to safely power on the drive, it could not be enabled to spin the motor. Enabling the drive required a further 24 VDC to be applied to the A3 terminal on the drive's I/O port along with two terminals on the Safe Torque Off port.

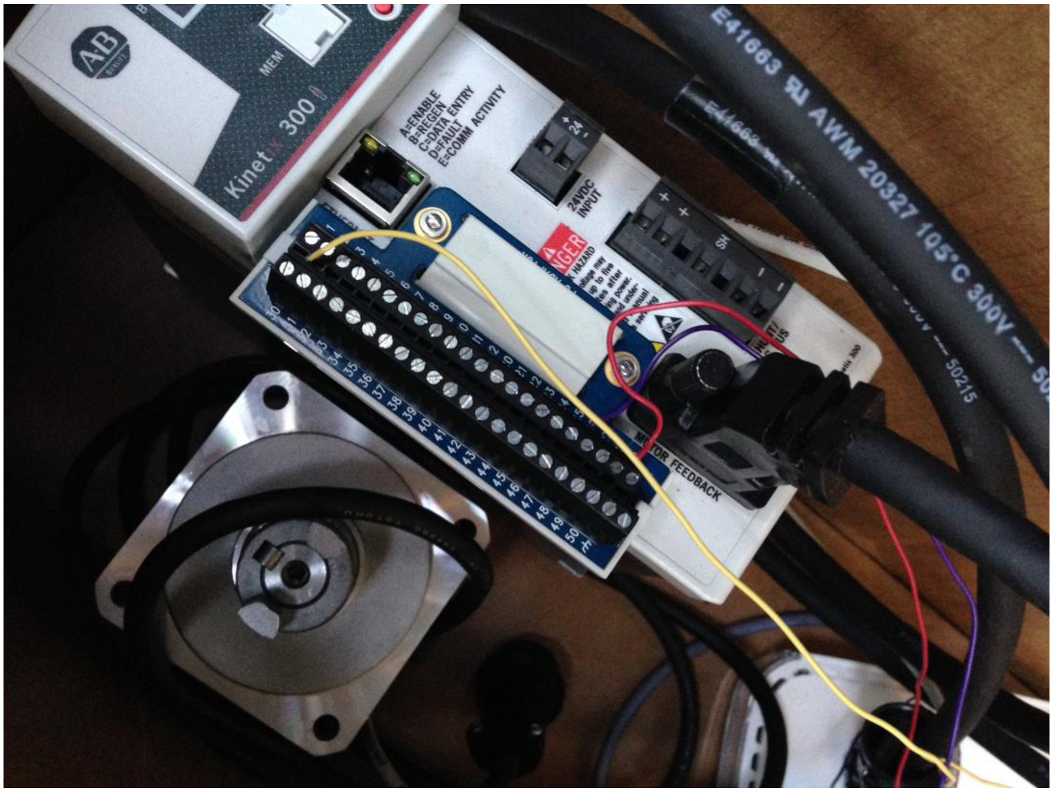


Figure 24. I/O Terminal Expansion Block with terminal A3 energized

The servo drive gives direct commands to the motor. The drive has a built in software, MotionView, which allowed for configuration of the drives 32 indices for a position, velocity, and acceleration. Using this method, 30 independent peaks were configured, giving 15 different cycles to create the pseudo-random motion desired, along with 2 indices used for homing the motor. Positions were chosen to replicate a pseudo-random sine wave with varied amplitudes ranging from small (2.64inch stroke, 3.2Hz) to large (11inch stroke, 1.6Hz).

6.1.6 Horizontal Electronics Development

The horizontal drive was initially planned to be open loop control with compression springs to keep the horizontal motion from drifting beyond the allowable range. However, the ease of use of the linear potentiometer enabled for a closed loop positional feedback design. One of the first tests conducted was calibration of the linear potentiometer. Then the relationship between the Arduino's analog reader signal and the extension length was correlated.

To drive the DC motor, the Pololu amplifier was connected to an external 12V power source and to the Arduno's PWM signal to control the speed. Once all the hardware was configured, the closed loop P controller on the Arduino was programmed. The early stages of controller design were done on temporary fixtures with tape that allowed the pinion to break away from the potentiometer in case the motor failed to stop before reaching the maximum extension of the potentiometer. The Kp gain was experimentally calibrated to create a sufficient position output with overshoot that did not exceed the operating distance of the potentiometer.

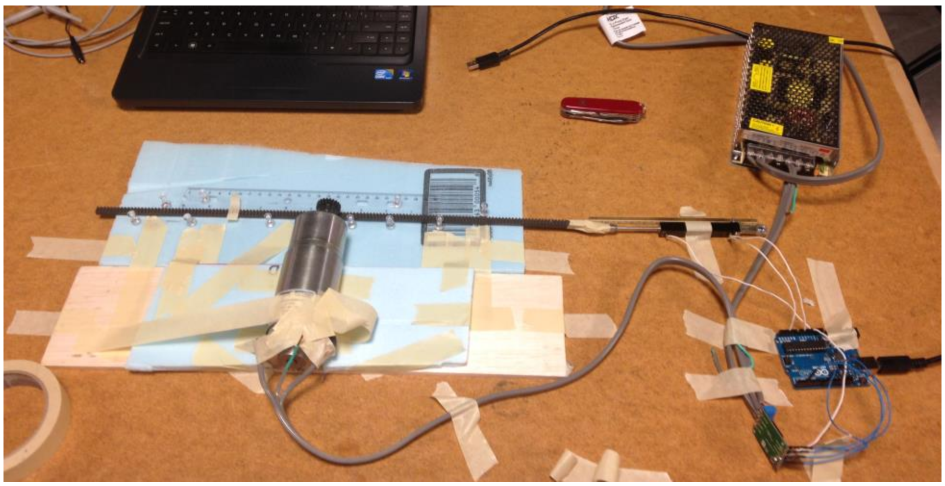


Figure 25. P controller test setup before hard mounting onto base plate.

With the position control finalized, a random position generator was created using the random number function inherent in C programming language. The random motion generator is random in the sense that the single next sinusoidal wave's amplitude and frequency was unpredictable, but there were restrictions on the range of possible amplitude and frequency values to match the project requirement. The code also allows for easy adjustment of the distribution of randomly chosen amplitudes with the default distribution being 70% small amplitudes (0.264inch stroke, 6.4Hz), 10% peak amplitudes (1.1inch stroke, 3.2 Hz), and 20% intermediate values that can vary from the minimum values to peak.

Lastly, the electronics and the DC motor were mounted onto the baseplate and tested for motor performance. At this stage a software-based stop limit that brakes the DC motor when the payload plate travels beyond the user-set safe limit was added into the code.

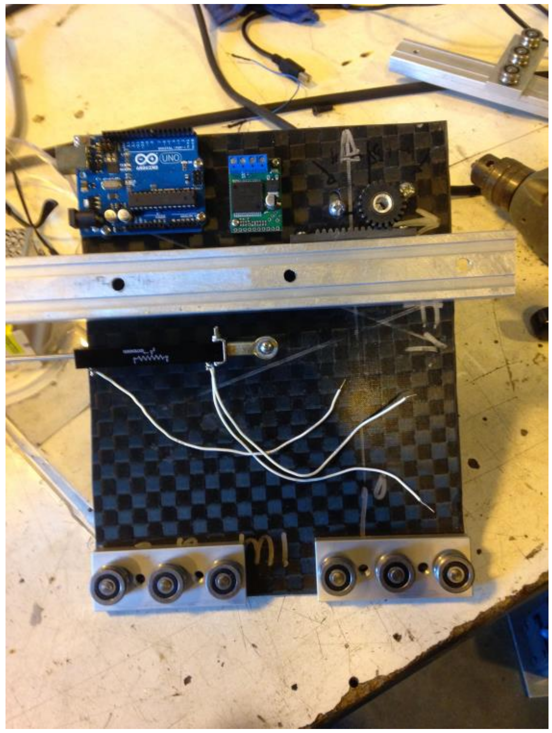


Figure 26. Backside of the payload plate showing the horizontal drive components.

6.2 Deviations from Final Design

Several deviations from the planned design occurred due to various part incompatibilities. Other changes to design benefitted the end result of the prototype.

6.2.1 Vertical Drive Controlled with Indices and Removed Need for PLC

Vertical drive does not use Ethernet communication in conjunction with PLC. The servo motor was originally intended to be powered by a servo drive with a PLC closing the loop and giving control to the system. After receiving the components however, the PLC turned out to not be capable of motion capabilities due to a lack of Pulse Train Output (PTO). The proper PLC for use with the Kinetix 300 drive, a CompactLogix controller, required purchasing software which was out of budget, so we had to change our control methods. Instead of incorporating a PLC into the system, we chose to use the servo drive to give direct commands to the motor. The drive has a built in software, MotionView, which allowed for configuration of the drives 32 indices for a position, velocity, and acceleration. Using this method, we configured 30 independent peaks, giving 15 different cycles to create the pseudo-random motion desired, along with 2 indices used for homing the motor.

6.2.2 Belt Tensioner Threading Method

The original plan for the belt tensioner was to have bolts run from the bottom of the tensioner to the top, with the axle for the pulley sitting on top of the end of the bolts to allow for adjustment. It was planned to simply tap the aluminum of the tensioner and have the bolts thread into that. It was later decided that aluminum threads would be insufficient for vibration resistance and replacing these threads with a nylock nut would work better. A small slot was cut in the side of the tensioner that intersected the bolt holes. These slots were sized such that the chosen nut would lightly press fit into the slot, preventing it from falling out of place should the bolts be removed. The nuts have steel threads, and a nylon lock so thread wear and vibration will not cause problems in the future.

6.2.3 Closed Loop Position Control for Horizontal

The planned design for the horizontal motion control involved an open loop controlled DC motor with two compression springs keeping the payload plate from drifting from the center as random torque was imparted on the rack and pinion. However, the Arduino and linear potentiometer configuration proved to be simple to implement positional feedback. Thus, a P controlled closed loop system was implemented to remove the need for springs to keep the payload from drifting.

6.2.4 Incorrect Part Sizes in CAD

Late in the design phase, we discovered that a more powerful servo was attainable with the limited budget, which prompted us to use a lower gear ratio gearbox and change the pinion size. However, this change did not get updated in the CAD model and the parts were ordered based on the old design. This affected the sizes for the motor-gearbox coupling, drive pulley size, and belt length. The correct sizes were purchased and the incorrect parts were returned to McMaster.

6.3 Recommendations for Future Manufacturing

During testing it was found that the originally installed drive pulley was too small, and needed to be replaced with a larger pulley, but there is not space for due to the presence of the base plate. Because the output shaft of the gearbox determines the height of the drive shaft, the gearbox would need to be shimmed away from the base plate or replaced with a taller gearbox in order to use a significantly larger pulley.

The axle about which the free pulley in the vertical belt drive system spins is a 0.25” steel rod, and bends slightly under the tension of the belt. It could be worthwhile to replace it with a larger diameter shaft to eliminate this bending, or use a stronger grade of steel.

The main drive shaft is constrained by two bearings and a rigid coupling in the current design. Either one of the bearings should be removed (not recommended) or the coupling should be replaced with a flexible coupling to avoid over constraining the system. This issue was mitigated in the current design by drilling the bearing mounting holes with significant clearance and fixing the bearings in place only after the shaft was attached to the gearbox output shaft.

A recommendation that became apparent while wiring all the electronics is to relieve stress on the connection points of all the wires. Primarily, the 12V power supply wire that feeds into the Pololu DC motor driver is susceptible to bending and could become weaker due to fatigue or slip out of the sockets. A method of clamping down the wires near the connection point should prevent the wires from bending.

7. DESIGN VERIFICATION

During the build process and after the completion of subassemblies and the full system, tests were conducted to ensure that components were working properly and assemblies were behaving as they were intended.

7.1 Test Descriptions and Results

7.1.1 Defining User Units

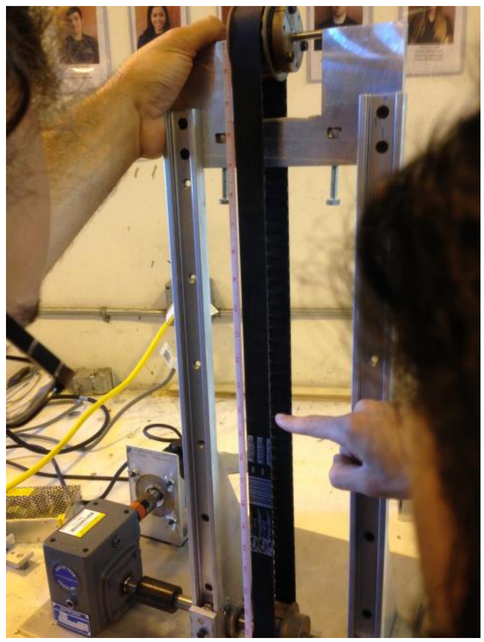


Figure 27. Comparing measured belt travel to desired travel distance.

The MotionView software that controls the Kinetix 300 servo drive has a built in user units function. Using it, the ratio of revolutions of the motor to our user units (inches) could be specified. This was calculated to be 2.5 rev/inch by taking into account the 20:1 reduction gear box and the size of the pulley used. This number was verified by commanding the motor to move 10 inches and measuring how far it actually moved via a marked location on the belt. Using this method, the position accuracy of the system in the vertical direction was confirmed to be within 1/16".

7.1.2 Linear Potentiometer Calibration

Before the linear potentiometer could be used for positional feedback, its relationship between extension length and resistance had to be measured. To achieve this, the potentiometer was connected to the Arduino's 5V output and ground and an oscilloscope was connected to the readout pin to measure the detected voltage. The linear potentiometer was rated to 1.5% tolerance and the verification using a ruler only permitted a resolution of 1/16", but the potentiometer was determined to be operating correctly.

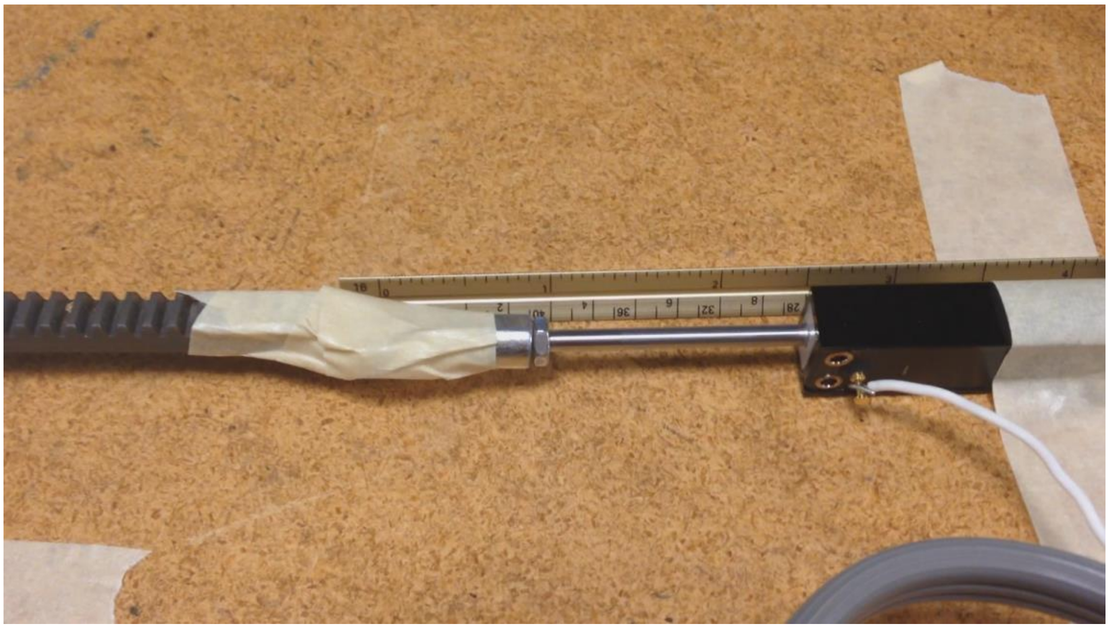


Figure 28. Correlating extension length to voltage readout.

7.1.3 Verifying Vertical Motion

The device is required to be able to create to different motion profiles defined by an amplitude and frequency each. These two modes were verified under no load by setting two indices at either peak of the maximum amplitude required and inputting the necessary velocities and accelerations to complete each motion's cycle at the given frequency. The amplitudes and frequencies were verified through MotionView's built in oscilloscope function which allowed monitoring of position and velocity, along with a variety of other inputs and outputs.

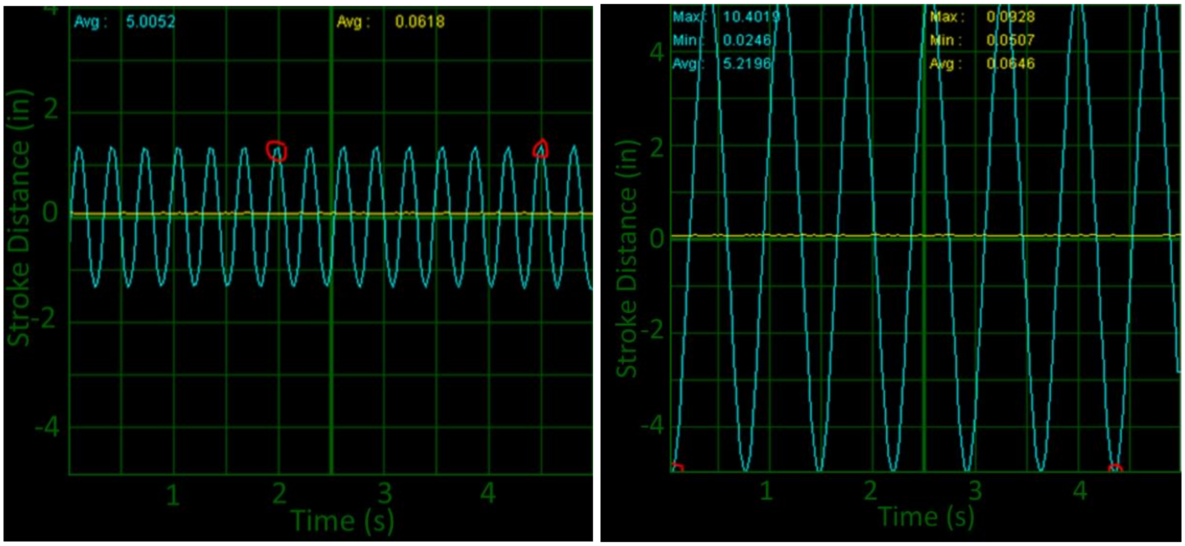


Figure 29. Oscilloscope plots that shows that the vertical drive system achieves the desired small (left) and large (right) amplitudes and frequencies.

7.1.4 Verifying Horizontal Motion

To test the horizontal motion response of the baseplate, an oscilloscope was connected to the linear potentiometer to measure the voltage readout while the device was in motion. The two required modes for horizontal motion were first tested independently by running a code that moved the payload in a constant sinusoidal motion.

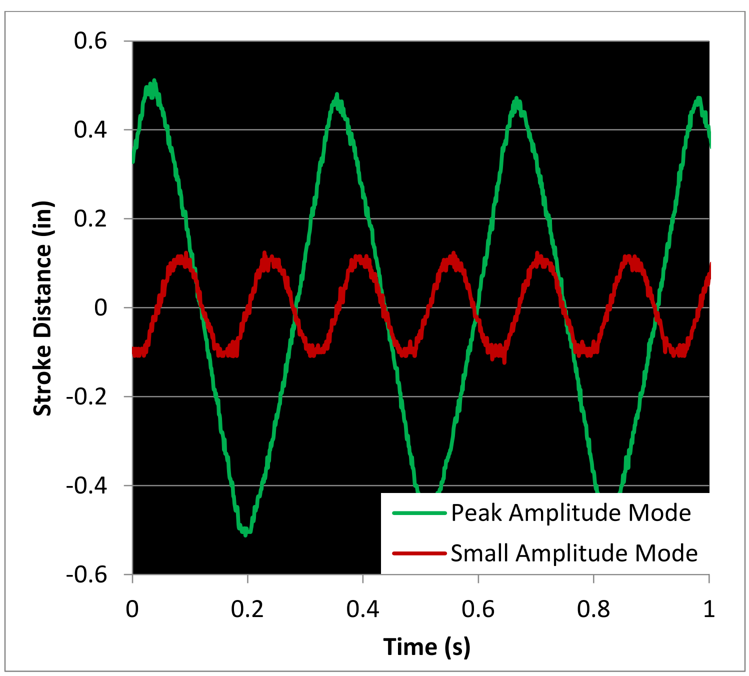


Figure 30. Oscilloscope plot that shows that the horizontal drive system achieves the desired small and large amplitudes and frequencies.

Once the two independent sine wave motions were verified to be operating correctly, the Arduino was set up to generate motions with random combination of the minimum to maximum spectrum of modes. Even when the horizontal axis was running in random mode, there were waves in the data that showed that the two desired wave frequencies were generated.

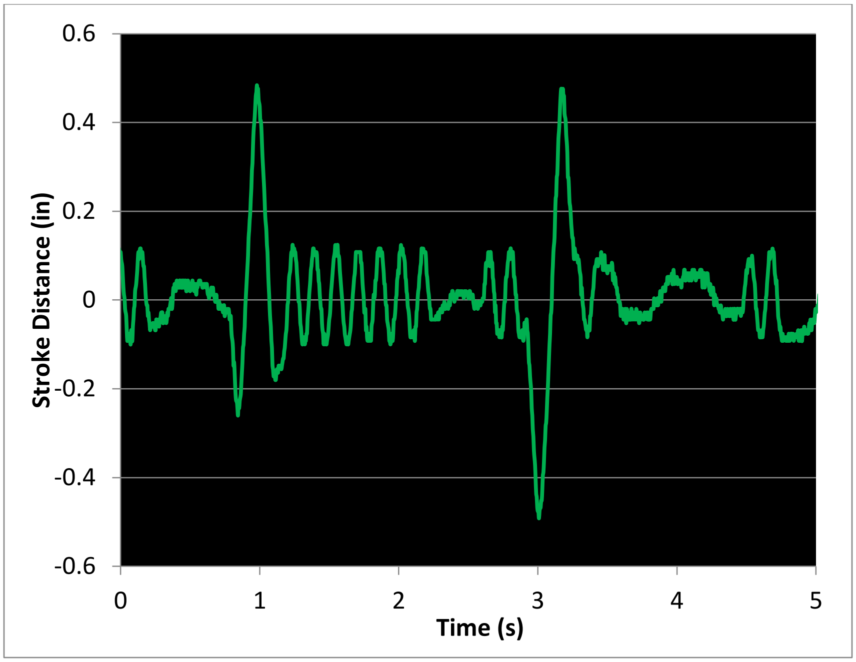


Figure 31. Oscilloscope plot showing the random motion generator in action and successfully outputting a random motion.

7.1.5 Verifying Combined Motion with Load

The combined motion test with loading has been postponed pending further input from the sponsor regarding information on the geometry and mounting hole location of the antenna. However, we are confident that they system will be able to meet the engineering requirements even with the 10 lb load due to the fact that the motors were selected with power significantly in excess of what was required by the system.

7.2 Specification Verification

For DVPR, see Appendix G – Design Verification Plan.

The table below gives an overview of which requirements were verified to be met with our final device. The requirement for no RF reflection is marked as incomplete because we do not have the low reflectivity foam nor access to an anechoic chamber for testing and believe that this is a requirement that will be easily met when Raytheon makes the necessary modifications. The user manual will be created after the publication of this report.

Table 4: Specification Checklist

Spec. # Parameter	Description	Requirement or Target	Tolerance	Compliance
1	Multi axis movement	2 axis of motion	Min	Yes
2	Can accelerate load in x and y axis	.6g in x, 1.4 in y	Min	Yes
3	Can produce 4 specific motion profiles	4 profiles	Min	Yes
4	Data refresh rate is 4-10 times bandwidth	30Hz	Min	Yes (According to DAQ Specsheet)
5	Impulses can be added that will extend vertical displacement	11in displacement	Min	Yes
6	No RF Reflection	Sensor only receives signals from transmitter	Max	Untested. Proper equipment and expertise missing
7	High expected lifetime	10000 cycles	Min	Yes
8	Can fit through door	3ft*7ft	Max	Yes
9	Accuracy	±5%	Max	±.01” accuracy or better in both axis
10	Accommodates payload	10lbs, 6in diameter	Min	Untested, but calculations include factor of safety and expected to pass
11	Cost	$5,000	Max	$4,625
12	Multiple independent tests per day	3 tests	Min	Yes
13	Impulses can be added that will extend horizontal displacement	1.1"	Min	Yes
14	Clarity of instructions	Able to fully operate system after 1 hour reading instructions	Max	Untested, but expected to pass without issue
15	Time to set up device	3 hours	Max	Approx. 40min

8. RECOMMENDATIONS AND CONCLUSIONS

Our wingtip dynamics simulator device successfully met most of the engineering requirements, and for the requirements that we were unable to directly verify, we are confident in our initial design which incorporated large factors of safety, and we expect the device to perform to satisfaction. We have attached a user's manual in Appendix J that will explain how to configure this device and operate it for testing.

Through the process of building and testing the device, we have observed some design choices that may be beneficial for Raytheon to consider and implement and have them listed below.

In the final design, the DC motor was mounted on the payload plate. This resulted in the motor needing to move its own mass in addition to the payload. This configuration also takes up space on the payload plate for mount holes and radio frequency absorbent foam. To remedy this, an attempt was made to mount the motor to the frame, but anywhere it could be mounted would have resulted in a collision sometime during the vertical cycle of motion. In future iterations of this device, an effort should be made to redesign the horizontal drive system so the motor is not attached to the front of the payload plate.

To create motion in the vertical direction, the drive is configured to rotate through its 32 indices, each having a position, velocity, and acceleration requirement. For actual randomized motion that could be programmed, it is recommended to purchase a CompactLogix PLC along with RSLogix 5000 programming software to implement in the servo control system.

In the current design, the electronics box is separate from the device's platform. To make transportation easier, the electronics box should be mounted on the same base plate as the rest of the device.

Lastly, this senior design project has given us hands-on experience with extensive background research, comprehensive design development, weeks of manufacturing, and quick adaptation to challenges. We are very proud of our work and are very thankful for the opportunity presented to us by Raytheon.

9. APPENDICES

Appendix A – References

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Appendix B – House of Quality

Explanation on the House of Quality:

The middle room of the House shows the strength of the relationships between customer requirements and derived specifications. It does this by marking which customer requirements each specification is related to and how strongly. The left and bottom sections rank each requirement in order of importance to the project and the customer. The right column lists currently available methods for solving the problem and their corresponding effectiveness at satisfying each customer requirement. Normally in this area, one of the columns is used to analyze the currently employed solution by the customer. However, since this is a new capability we are testing, there are no previous solutions to use as a baseline. The roof shows the positive and negative interactions the requirements have on one another. If satisfying one specification makes it harder or easier to satisfy another, then that relationship is marked here. From the Technical Importance Rating found in the QFD, we were able to distinguish which factors were most important to our design and which were negligible. For example, the QFD showed that the amplitude and control of the input motion were of high priority, whereas minimizing the RF emissions was not as pertinent.

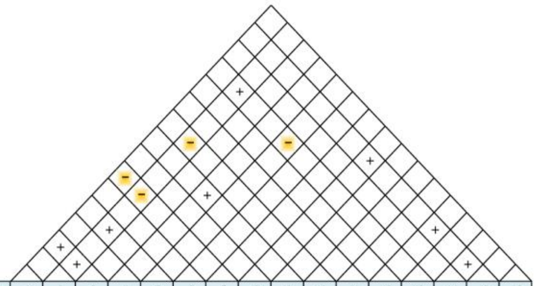
Table 5. House of Quality Overview.

QFD: House of Quality
Project:
Revision:
Date:

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



WHO: Customers

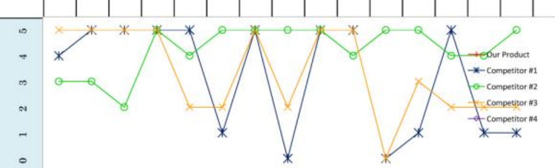
Row #	Weight Chart	Relative Weight	Raytheon software engineers	Pilot	Raytheon Technician		Maximum Relationship	WHAT: Customer Requirements (explicit & implicit)
1		11%	5	8	3		9	2 Axis System
2		9%	2	5	6		9	Selectable motion and frequency up to 11" and 7Hz
3		10%	5	7	2		9	Random amplitude and phase inputs added
4		8%	7	3	3		9	Real time knowledge of motion
5		13%	8	9	1		9	Simulate flight conditions of wingtip
6		6%	6	1	3		9	RF doesn't interfere with test system
7		8%	3	1	9		9	Reusable test machine
8		8%	3	1	9		9	Can be transported to Raytheon facility
9		12%	7	5	7		9	Mount payload on device
10		6%	6	1	3		9	Must be a reasonable price
11		8%	3	1	9		9	Quick setup time and turn around rate
12		0%						
13		0%						
14		0%						
15		0%						
16		0%						

HOW: Engineering Specifications

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Direction of Improvement	◇	▲	◇	▲	◇	▼	▲	▼	▼	◇	▼	▲	▲	▲	▼	
Row # / WHAT	Multi-axis movement	Accelerate load in x and y axis	Can produce 4 specific motion profiles	Data refresh rate is 4-10 times bandwidth	Impulses can be added that will extend vertical displacement	Low RF emissions	High expected lifetime	Can fit through door	Accuracy of position, velocity, and acceleration	Accomodates payload	Cost	Multiple independent tests per day	Impulses can be added that will extend horizontal displacement	Clarity of Instructions	Time to set up device	
1	●		○		○						▽		○			
2	○	●	●		●					▽			●			
3		●	○		●								●			
4				●					●							
5	●	●	●		●				○				●			
6						●										
7							●				○	●				
8								●							▽	
9										●		▽			●	
10											●	▽				
11												●		●	●	
12																
13																
14																
15																
16																
HOW MUCH: Target	2 axis	0.74g (vertical) 0.3g (horizontal)	4 profiles	Greater than 30Hz	11" peak to peak displacement	RF noise less than 1kHz	1000 cycle use	Fit through 3'x7' door	Data error +-1%	Support 10lbs/6"dia	Less than $15,000	Perform 3 tests per day	1.1" peak to peak displacement	Working knowledge of device after an hour of instruction	3 hours	
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	
Technical Importance Rating	240.6	280.9	255.7	75.97	314.5	56.23	72.6	72.6	113.8	120.9	91.63	163.9	314.5	72.6	192.7	
Relative Weight	10%	12%	10%	3%	13%	2%	3%	3%	5%	5%	4%	7%	13%	3%	8%	
Weight Chart																

Current Product Assessment - Engineering Specifications

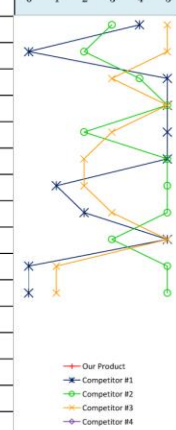
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Our Product: N/A																
Competitor #1: *Flight Testing*	4	5	5	5	5	1	5	0	5	5	0	1	5	1	1	
Competitor #2: *Intern Actuated*	3	3	2	5	4	5	5	5	5	4	5	5	4	4	5	
Competitor #3: *Robot Actuated*	5	5	5	5	2	2	5	2	5	5	0	3	2	2	2	



Column # 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

NOW: Current Product Assesment - Customer Requirements

Row #	Our Current Product: N/A	Competitor #1:Flight Testing	Competitor #2: *Intern Actuated*	Competitor #3: *Robot Actuated*		Row #
1		4	3	5		1
2		0	2	5		2
3		5	4	3		3
4		5	5	5		4
5		5	2	3		5
6		5	5	2		6
7		1	5	2		7
8		2	5	3		8
9		5	3	5		9
10		0	5	1		10
11		0	5	1		11
12						12
13						13
14						14
15						15
16						16



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Date: 4/23/2010
Christopher Battles

Table 6. Roof of House of Quality.

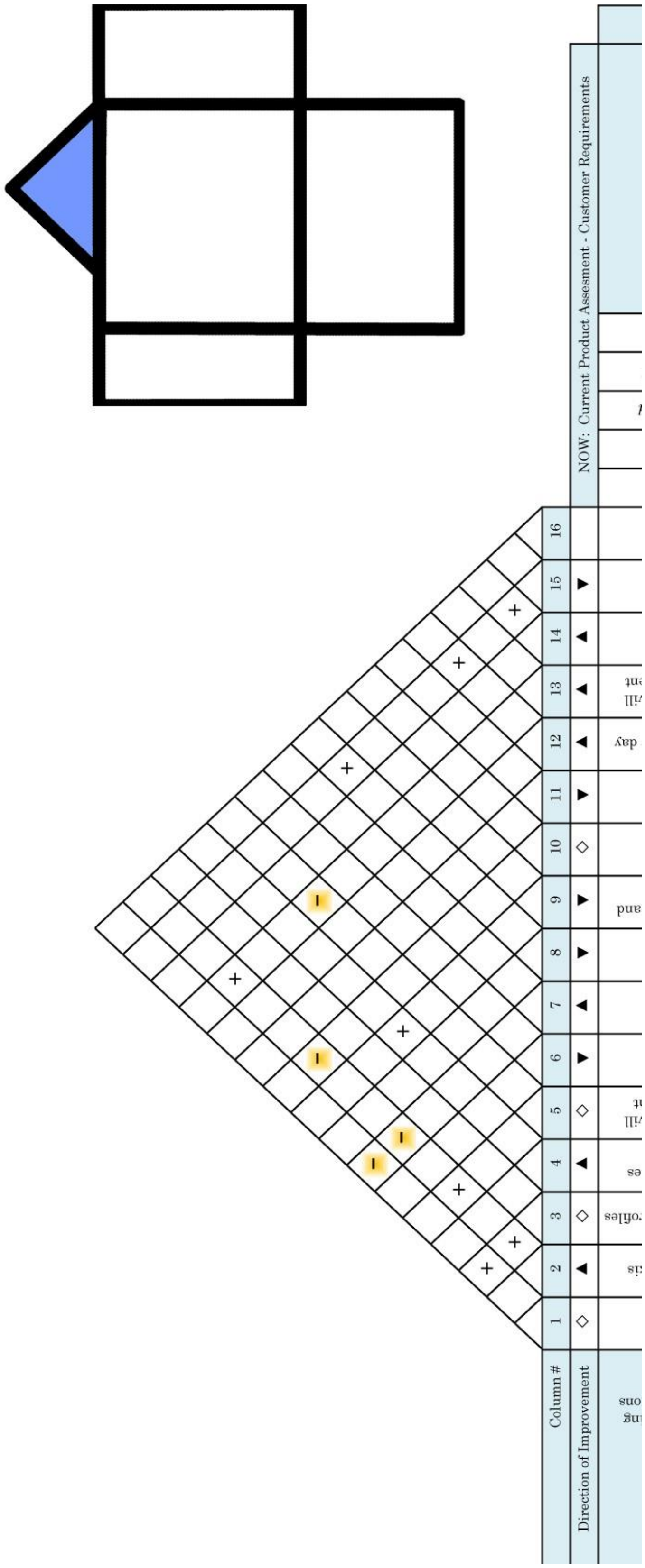
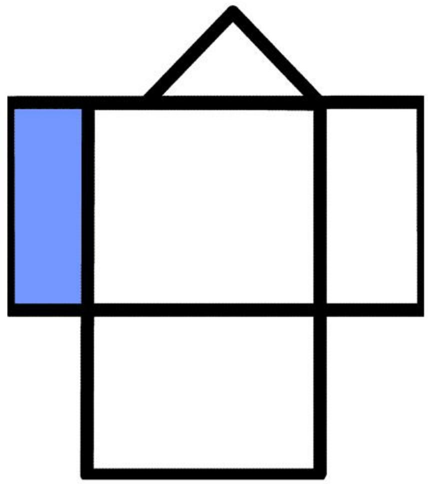


Table 7. Left side of House of Quality.

QFD: House of Quality
Project:
Revision:
Date:



Correlations	
Positive	+
Negative	−
No Correlation	

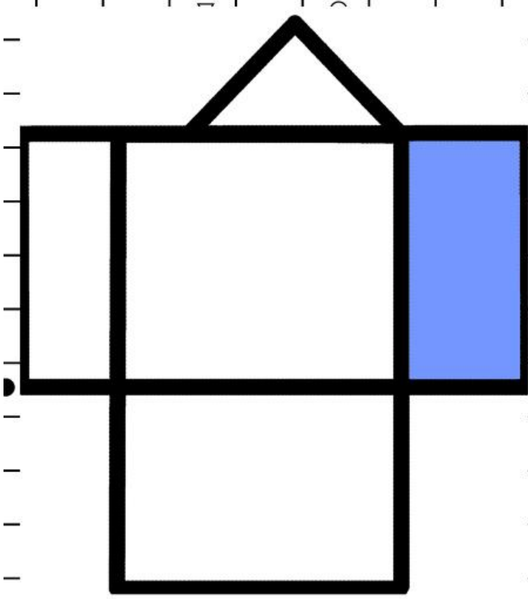
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

			WHO: Customers					Column #	1
								Direction of Improvement	◇
Row #	Weight Chart	Relative Weight	Raytheon software engineers	Pilot	Raytheon Technician		Maximum Relationship	WHAT: Customer Requirements (explicit & implicit) / HOW: Engineering Specifications	Multi-axis movement
1		11%	5	8	3		9	2 Axis System	●
2		9%	2	5	6		9	Selectable motion and frequency up to 11" and 7Hz	○
3		10%	5	7	2		9	Random amplitude and phase inputs added	
4		8%	7	3	3		9	Real time knowledge of motion	
5		13%	8	9	1		9	Simulate flight conditions of wingtip	●
6		6%	6	1	3		9	RF doesn't interfere with test system	
7		8%	3	1	9		9	Reusable test machine	
8		8%	3	1	9		9	Can be transported to Raytheon facility	
9		12%	7	5	7		9	Mount payload on device	
10		6%	6	1	3		9	Must be a reasonable price	
11		8%	3	1	9		9	Quick setup time and turn around rate	
12		0%							
13		0%							
14		0%							
15		0%							
16		0%							

Table 8. Right side of House of Quality.

Column #	8	9	10	11	12	13	14	15	16
Direction of improvement	▼	▼	◇	▼	▲	▲	▲	▼	
Functional requirement	Can fit through door	Accuracy of position, velocity, and acceleration	Accomodates payload	Cost	Multiple independent tests per day	Impulses can be added that will extend horizontal displacement	Clarity of Instructions	Time to set up device	



NOW: Current Product Assesment - Customer Requirements

Row #	Our Current Product: N/A	Competitor #1:Flight Testing	Competitor #2: *Intern Actuated*	Competitor #3: *Robot Actuated*
1		4	3	5
2		0	2	5
3		5	4	3
4		5	5	5
5		5	2	3
6		5	5	2
7		1	5	2
8		2	5	3
9		5	3	5
10		0	5	1
11		0	5	1
12				
13				
14				
15				
16				

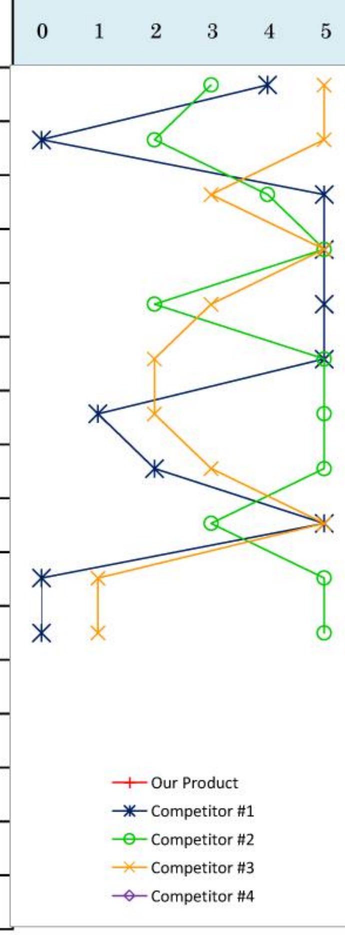
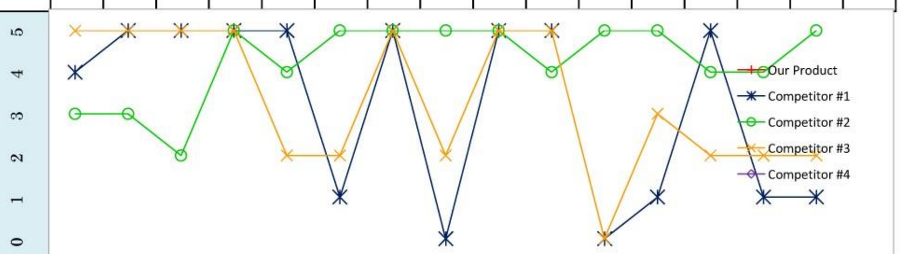
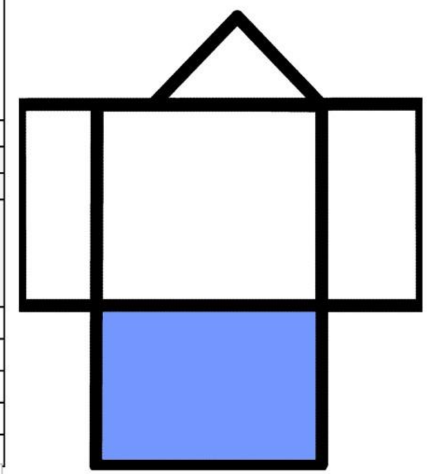


Table 9. Bottom of House of Quality.

HOW MUCH: Target	2 axis	0.74g (vertical) 0.3g (horizontal)	4 profiles	Greater than 30Hz	11" peak to peak displacement	RF noise less than 1kHz	1000 cycle use	Fit through 3'x7' door	Data error +-1%	Support 10lbs/6"dia	Less than $15,000	Perform 3 tests per day	1.1" peak to peak displacement	Working knowledge of device after an hour of instruction	3 hours	
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	
Technical Importance Rating	240.6	280.9	255.7	75.97	314.5	56.23	72.6	72.6	113.8	120.9	91.63	163.9	314.5	72.6	192.7	
Relative Weight	10%	12%	10%	3%	13%	2%	3%	3%	5%	5%	4%	7%	13%	3%	8%	
Weight Chart																
Our Product: N/A																
Competitor #1: *Flight Testing*	4	5	5	5	5	1	5	0	5	5	0	1	5	1	1	
Competitor #2: *Intern Actuated*	3	3	2	5	4	5	5	5	5	4	5	5	4	4	5	
Competitor #3: *Robot Actuated*	5	5	5	5	2	2	5	2	5	5	0	3	2	2	2	
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Current Product Assesment - Engineering Specifications





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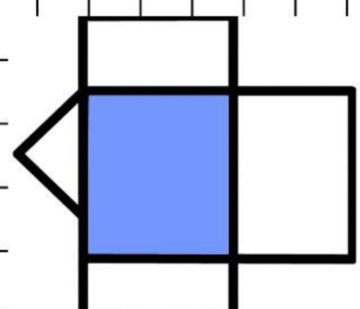
Christopher Battles
Date: 4/23/2010

Table 10. Center of House of Quality.

WHAT: Customer Requirements (explicit & implicit) / HOW: Engineering Specifications	Multi-axis movement	Accelerate load in x and y axis	Can produce 4 specific motion profiles	Data refresh rate is 4-10 times bandwidth	Impulses can be added that will extend vertical displacement	Low RF emissions	High expected lifetime	Can fit through door	Accuracy of position, velocity, and acceleration	Accomodates payload	Cost	Multiple independent tests per day	Impulses can be added that will extend horizontal displacement	Clarity of Instructions	Time to set up device		Our Current Product: N/A	Competitor #1:Flight Testing	Competitor #2: *Intern Actuated*	Competitor #3: *Robot Actuated*
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	NOW: Current Product As			
Direction of Improvement	◇	▲	◇	▲	◇	▼	▲	▼	▼	◇	▼	▲	▲	▲	▼					
2 Axis System	●		○		○						▽		○					4	3	5
Selectable motion and frequency up to 11" and 7Hz	○	●	●		●					▽			●					0	2	5
Random amplitude and phase inputs added		●	○		●								●					5	4	3
Real time knowledge of motion				●					●									5	5	5
Simulate flight conditions of wingtip	●	●	●		●				○				●					5	2	3
RF doesn't interfere with test system						●												5	5	2
Reusable test machine							●				○	●						1	5	2
Can be transported to Raytheon facility								●							▽			2	5	3
Mount payload on device										●		▽			●			5	3	5
Must be a reasonable price											●	▽						0	5	1
Quick setup time and turn around rate												●		●	●			0	5	1



Appendix C – Weighted Design Matrix

Table 11. Weighted Decision Matrix.

Criteria \ Concept	Weight	Crank w/ Spring		Actuator w/Spring		Mechanical Actuator	
		Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted
Variable Amplitude	0.22	75	16.5	90	19.8	100	22
Create multiple profiles	0.17	75	12.75	90	15.3	100	17
Maximum velocity	0.06	90	5.4	90	5.4	80	4.8
Control of driving frequency	0.19	90	17.1	100	19	100	19
Response Time of payload	0.08	75	6	80	6.4	100	8
Configurability	0.08	70	5.6	80	6.4	90	7.2
Life Time	0.03	90	2.7	80	2.4	80	2.4
Price	0.03	90	2.7	75	2.25	40	1.2
Complexity	0.14	50	7	60	8.4	80	11.2
ΣS	1	705	75.75	745	85.35	770	92.8

Weighted Design Matrix Criteria Definitions

Variable Amplitude-Ease of impulse introduction to change the payload amplitude throughout the run

Create Multiple Profiles-Ease of creating a new profile to operate at

Control of Driving Frequency-Ease to change frequency of actuation

Response Time of Payload-How quickly the payload responds to a new impulse

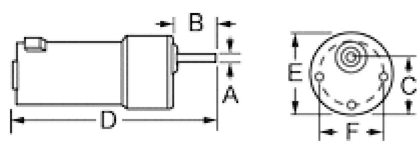
Configurability-Ease to set up a new profile in between runs

Complexity-Complexity of components and design including analysis, modeling, and construction

Appendix D – Design Analysis

Table 12. Servo motor specs for vertical axis

Catalog Number	Rated Speed rpm	Rated Output kW	Rotor Inertia* kg-m^2 (lb-in.-s^2)	Continuous Stall Torque Nm (lb-in.)	Peak Stall Torque Nm (lb-in.)	Continuous Stall Current Amperes (0-peak)	Peak Stall Current Amperes (0-peak)	Motor Weight kg (lb)
TLY-A230T	6000	0.44	0.000034 (0.0003)	1.300 (11.50)	3.05 (27.0)	5.50	15.5	1.3 (2.87)



rpm	Torque, in.-lbs.	(A)	(B)	(C)	(D)	(E)	Bolt Hole Circle (F)	Mounting Holes (Qty.)	Full Load Amps		Each
12 VDC											
179	23.38	0.25"	0.75"	1.39"	6.30"	2.125"	1.5"	10-32 (2)	5.74	2709K17*	$254.92

Table 13. DC motor specs for horizontal axis.

Analysis – Motion Requirements

Dynamica

Vertical Requirements:	Amplitude ($\frac{\text{peak-peak}}{2}$)	Frequency	V_{max}	a_{max}
Mode 1	2.68 in	3.2 Hz	26.9 in/s	1.4g
Mode 2	5.5 in	1.6 Hz	55.3 in/sec	1.4g
Horizontal Requirements:				
Mode 1	0.268 in	6.4 Hz	5.39 in/s	0.6g
Mode 2	0.55 in	3.2 Hz	11.0 in/s	0.6g

Max Velocity Sample Calc for Mode 2 Vertical Axis

$V(t) = -A\omega_n \cos(\omega_n t + \phi)$

$V_{max} = A\omega_n$

$V_{max}(\text{Vertical Mode 2}) = 5.5\text{ in} \times \left(1.6\text{ Hz} \cdot \frac{2\pi\text{ rad}}{\text{cycle}}\right)$

$V_{max_{V2}} = 55.3\text{ in/sec}$

Max Acceleration Sample Calc for Mode 2 Vertical Axis

$a(t) = \frac{dV}{dt} = A\omega_n^2 \sin(\omega_n t + \phi)$

$a_{max} = A\omega_n^2$

$a_{max}(\text{V Mode 2}) = 5.5\text{ in} \times \left(1.6\text{ Hz} \times \frac{2\pi\text{ rad}}{\text{cycle}}\right)^2 \times \frac{1\text{ ft}}{12\text{ in}}$

$a_{max} = 46.3\text{ ft/sec} \times \frac{1g}{32.2\text{ ft/s}}$

$a_{max} = 1.4g$

Analysis - Motor Sizing

Dynamica

Vertical

Calculation for required force applied at belt

$W_{payload+carriage} = 15 lbf$

$F_{belt\ up} = W*(a_{max}+1g) = 15 lbf \times (1.4g+1g)$

$F_{belt\ up} = 36.6 lbf$

Calculation for required motor horsepower

$P_{motor} = F_{belt\ up} * V_{max}$

$P_{motor} = 36.6 lbf \times 55.3 \frac{in}{sec} \cdot \frac{1 ft}{12 in} \cdot \frac{60 sec}{1 min} \cdot \frac{1 hp}{33{,}000 \frac{ft \cdot lbf}{min}}$

$P_{motor} = 0.31 hp$ (Vertical)

Horizontal

Force at rack

$W = 13 lbf$

$F_{rack} = W * a_{max} = 13 lbf \times 0.6g$

$F_{rack} = 7.47 lbf$

Motor horsepower

$P_{motor} = F_{rack} * V_{max}$

$P_{motor} = 7.47 lbf \times 11.0 \frac{in}{s} \cdot \frac{1 ft}{12 in} \cdot \frac{60 sec}{1 min} \cdot \frac{1 hp}{33{,}000 ft \cdot lbf / min}$

$P_{motor} = 0.0125 hp$ (horizontal)

Analysis - Motor Selection

Dynamica

Vertical

TLY-230 Motor (Allen-Bradley)

- Continuous Stall Torque = 11.5 in-lb
- Speed = 5000 RPM
- Power: Torque (in-lb) × Speed (RPM) · $\frac{1 ft}{12 in} \cdot \frac{1 hp}{5252 ft \cdot lb \cdot RPM}$

  Power: 0.59 hp > 0.31 hp required

Horizontal

12 V DC Geared Motor (McMaster)

- Continuous Stall Torque = 23.38 in-lb
- Speed = 197 RPM
- Power = 0.073 hp > 0.0125 hp required

Analysis – Drive and Controller Selection

Dynamica

Vertical

- Kinetix 3 Servo Drive
  - Compatible with TLY Motors
  - 400 W Power Rating
    - TLY-230 Power = 0.59 hp $\left(\frac{746\ W}{1\ hp}\right)$ = 440W
    - Drive can sufficiently power motor but can't output power that will exceed motor's rating
- Micrologix 1100 PLC
  - Compatible with Kinetix 3 Servo Drive

Horizontal

DC Motor: 12V, 5.91 Amps

- Pololu Motor Driver
  - Can deliver 12A continuously (5.74 req.)
  - Operates from 5.5-24V (will drive 12V motor)
  - PWM up to 20kHz (sufficient for electric motors)
  - Built in protection against reverse voltage from motor.

Analysis- Gear Bending Stress

Dynamica

Vertical

Note: All tables from Mechanical Engineering Design, 9th Edition (Shigley)

Drive Pulley

$N = 16$ teeth $F = 1\frac{1}{16}$ in

$d_p = 2.546$ in $P = \frac{N}{d_p} = 6.28 \frac{\text{teeth}}{\text{in}}$

Table A-22

$S_y = 32$ksi (1018 steel)

Figure 14-6

$J = 0.27$

Table 14-2

$Y = 0.296$ (16 teeth)

AGMA Stress equation

$$\sigma = W^t K_o K_v K_s \frac{P_d}{FJ}$$

K_o, overload factor = 1.50 due to overloading (figure 14-17)

$$V = \frac{\pi d n}{12} = \frac{\pi (2.546\text{in})(387.8\text{RPM})}{12}$$

$V = 258.5$ fpm

$$K_v = \frac{1200 + V}{1200} = \frac{1200 + 258.5}{1200} = 1.23$$

$$W^t = \frac{H(33{,}000)}{V} = \frac{0.306\text{hp}(33{,}000)}{258.5\text{fpm}} = 39.116$$

$$K_s, \text{size factor} = 1.192\left(\frac{F\sqrt{Y}}{P}\right)^{0.0535}$$

$$K_s = 1.192\left(\frac{1\frac{1}{16}\text{in}\sqrt{0.296}}{6.28}\right)^{0.0535}$$

$K_s = 1.05$

$$\sigma = \frac{(39.116)(1.50)(1.23)(1.05)(6.28\tfrac{1}{\text{in}})}{(1\tfrac{1}{16}\text{in})(0.27)}$$

$\sigma = 1658.2$ psi

$$N = \frac{S_y}{\sigma} = \frac{32\text{ksi}}{1658.2\text{psi}}$$

N = 19, factor of safety

GEARBOX SIZING

INPUT hp = 0.31 hp
SERVO SPEED = 5000 RPM

GEARBOX hp = 0.52 hp
MAX SPEED = 4500 RPM
RATIO = 20:1

ANALYSIS

OUTPUT SPEED @ 4500 RPM = 225 RPM

INPUT hp IS LESS THAN RATED GEARBOX VALUE.

AMPAD

RACK & PINION SELECTION

MOTOR MAX SPEED = 179 rpm
TORQUE = 7.75 lb-in.
HORIZONTAL MOTION REQ'D = 11.0 in/s

FIND
PINION DIAMETER

ANALYSIS

$$179 \text{ RPM} \left[\frac{1 \text{ min}}{60 \text{ sec}}\right] = 2.98 \text{ rps}$$

$$11 \text{ in/s} \div 2.983 \text{ rps} = 3.70 \frac{\text{in}}{\text{cycle}}$$

$$3.70 \frac{\text{in}}{\text{cycle}} \left[\frac{1 \text{ cycle}}{2\pi \text{ rad}}\right] = 0.587 \text{ in DIAMETER}$$

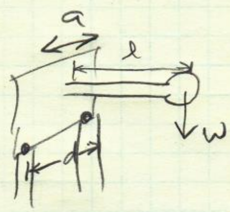
TWISTING MOMENT FROM HORIZONTAL MOVEMENT

$W = 10\,lb$

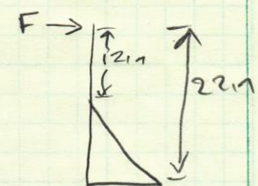
$l = 1\,ft$

$a = 0.6g$

$d = 9\,in$



SIDE VIEW



ANALYSIS

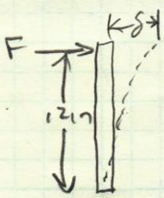
$$\text{MOMENT} = (W)(a) \times l = (10\,lbs)(0.6)(1\,ft) = 6\ ft\text{-}lb$$

RAILS 6 in APART

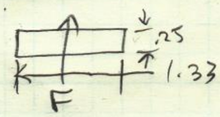
FORCE ON ONE RAIL:

$$F = \frac{6\,ft\text{-}lb}{6\,in\left[\frac{1\,ft}{12\,in}\right]} = 12\,lbf$$

ASSUMING THAT THE SUPPORTED LOWER HALF OF THE RAIL IS RIGID, THE BEAM DEFLECTION OF THE TOP IS ESTIMATED AS:



X-SECTION (SIMPLIFIED)



$$I = \frac{1}{12}(0.25)^2(1.33)$$

$$= 6.93 \times 10^{-3}\,in^4$$

$$\delta_{max} = \frac{Pl^3}{3EI} = \frac{(12\,lb)(12\,in)^3}{3\left(10\times10^6\,\frac{lb}{in^2}\right)\left(6.93\times10^{-3}\,in^4\right)} = \boxed{1.44 \times 10^{-5}\,in}$$

VERTICAL CARRIAGE LOAD

$W_{toc} = 15\ lbf$

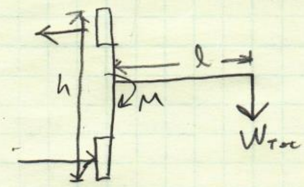
$l = 15\ in$

$h = 9.5\ in$

$Width = 7.25\ in$

$a = 2.44g$

MAX DYNAMIC LOAD = 336 lbf



ANALYSIS

$M = (15\ lbf \times 2.44g) \times 15\ in \left[\frac{1\ ft}{12\ in}\right]$

$M = 45.75\ ft\text{-}lb$

$\frac{h}{2} = 4.75\ in$

$F_2 = 115.6\ lb$

$\boxed{\frac{F_2}{2} = 57.79\ lb}$

LESS THAN MAX LOAD ON CARRIAGE (336 lbf)

$\boxed{S.F. = 5.8}$

PULLING FORCE AT BASEPLATE BOLTS.

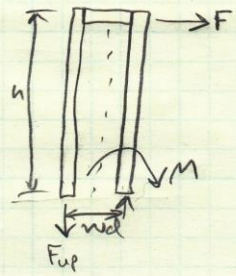
W = 15 lbs (PAYLOAD + PLATE)

a = 0.6g

h = 22 in

wd = 8 in

3x 10-32 BOLTS ON EACH SIDE



ANALYSIS

$F = W \cdot a = (15\,lbf)(0.6) = 9.6\ lb$

$M = 211.2\ lb\text{-}in$

$F_{up} = \frac{211.2\ lb\text{-}in}{3\,in} = 70.4\ lb = F_{up}$

$F_{BOLT} = \frac{70.4\ lb}{3} = 23.4\ lb/_{BOLT} = F_{BOLT}$

SINCE SCREWS ARE STEEL, BUT ANGLE SUPPORT IS ALUMINUM, CHECK FOR ALUMINUM INTERNAL THREAD PULLOUT.

$$A_n \begin{pmatrix}\text{INTERNAL}\\ \text{SHEAR AREA}\end{pmatrix} = \pi n L_e D_{s\,min}\left(\frac{1}{2n} + 0.57735\left(D_{s\,min} - E_{n\,max}\right)\right)$$

WHERE: $E_{n\,max}$ = MAX PITCH DIAMETER OF INTERNAL THREAD

$D_{s\,min}$ = MIN MAJ DIAM OF EXTERNAL THREAD

L_e = FASTENER THREAD ENGAGEMENT

n = # OF THREADS/in.

$$A_n = \pi(32T/in)(.50in)(0.1831in)\left[\frac{1}{2n} + 0.57735(0.1831in - 0.1736in)\right]$$

$A_N = 1.5152\,in^2$

$$\sigma_{INTERNAL} = \frac{F_{BOLT}}{A_N} = \frac{23.4\ lb}{1.5152\,in^2} = 15.44\ psi$$

ALUMINUM'S TENSIL STRENGTH IS 45000 psi

∴ NO RISK OF BOLT PULLOUT.

Appendix E – Bill of Materials

Name	Part #	Source	Cost	Count	Tax	Shipping	Total
Servo Motor	TLY-A2530P-HJ62AA	Allen-Bradley	$374.44	1			$374.44
Micro Logix 820 PLC	2080-LC20-20QBB	Allen-Bradley	$249.00	1			$249.00
Kinetix 300 Drive	2097-V31PR2	Allen-Bradley	$836.00	1			$836.00
Power Cable	2090-CPWM6DF-16AA02	Allen-Bradley	$62.10	1			$62.10
Feedback Cable	2090-CFBM6DD-CCAA02	Allen-Bradley	$110.00	1	$124.00	$21.85	$255.85
Terminal Expansion Block	2097-TB1	Allen-Bradley	$148.00	1	$12.06	$12.76	$172.82
Linear Encoder	N/A	SRA Measurement Products	$220.44	1		$13.62	$234.06
Ethernet Switch	N/A	Best Buy	$34.99	1			$34.99
Ethernet Cable	N/A	Best Buy	$4.99	3	$4.00		$18.97
10 gauge wire	N/A	Home Depot	$1.32	4			$5.28
10-4 SOOW Cord	N/A	Home Depot	$8.37	1			$8.37
60 Amp Main Lug Surface	N/A	Home Depot	$13.97	1			$13.97
Clamp Connector	N/A	Home Depot	$4.09	1			$4.09
20A 2 Pole Circuit Breaker	N/A	Home Depot	$9.47	1	$4.49		$13.96
Power Supply Cord	N/A	Home Depot	$8.47	1	$0.68		$9.15
20A 250V Plug	N/A	Home Depot	$11.87	1	$0.95		$12.82
24VDC Power Supply	N/A	Amazon	$17.47	1		$3.99	$21.46
Gearbox	5887K251	McMaster-Carr	$369.69	1	$27.73	$10.04	$407.46
Drive Shaft	1497K141	McMaster-Carr	$19.67	1			$19.67
Free Shaft	6061K107	McMaster-Carr	$4.62	1			$4.62
Input Coupling	6408K11	McMaster-Carr	$3.61	2			$7.22
Input Coupling Spider	6408K84	McMaster-Carr	$2.35	1			$2.35
Output Coupling	6412K42	McMaster-Carr	$15.55	1			$15.55
24" Rails	6738K73	McMaster-Carr	$54.96	1			$54.96
1/4"-28 Screws	91251A435	McMaster-Carr	$8.68	1			$8.68
Drive Pulley	6495K46	McMaster-Carr	$59.41	1	$4.46	$8.31	$72.18
Drive Pulley(unreturnable)	6495K44	McMaster-Carr	$47.69	1			$47.69
Follower Pulley	6495K511	McMaster-Carr	$36.20	1			$36.20
Bearings	5912K17	McMaster-Carr	$13.33	2			$26.66
10-32 Screw	91253A008	McMaster-Carr	$11.05	1			$11.05
1/4" Aluminum	8982K81	McMaster-Carr	$22.05	1			$22.05

Plate (90)							
Aluminum Spacers	92510A182	McMaster-Carr	$1.90	8			$15.20
1/4" Aluminum Base Plate	89155K27	McMaster-Carr	$92.21	1			$92.21
1/2" Aluminum	9057K252	McMaster-Carr	$78.19	1			$78.19
1/4"-20 Screw	91309A562	McMaster-Carr	$6.16	1			$6.16
Carriage	6738K41	McMaster-Carr	$58.33	8			$466.64
3/8" Aluminum	8975K213	McMaster-Carr	$20.34	1			$20.34
Rack	6295K12	McMaster-Carr	$21.17	1			$21.17
Pinion	6325K64	McMaster-Carr	$21.57	1			$21.57
36" Rails	6738K73	McMaster-Carr	$82.44	1			$82.44
12" Rails	6738K74	McMaster-Carr	$27.48	1			$27.48
DC Motor	2709K17	McMaster-Carr	$249.44	1	$105.98	$23.76	$379.18
1/2" Bushing	6086K111	McMaster-Carr	$12.24	1			$12.24
Ball Bearing	57155K304	McMaster-Carr	$5.62	2			$11.24
56" Timing Belt	6484K412	McMaster-Carr	$40.78	1	$4.82	$7.81	$53.41
Microcontroller	Arduino Uno R3	Adafruit Industries	$24.95	1		$6.68	$31.63
Speed Controller	VNH5019 Motor Driver	Pololu	$24.95	1		$3.95	$28.90
Potentiometer	LCP12Y50-1K	Potentiometer.com	$142.50	1		$30.00	$172.50
12VDC Power Supply	N/A	Amazon	$16.39	1			$16.39
Power Supply Cord	N/A	Home Depot	$8.47	1			$8.47
Lock nut/Screw	N/A	Home Depot	$1.18	2	$0.87		$3.23
Electrical Supplies	N/A	Miners	$7.50	1	$0.61		$8.11
Fasteners	N/A	Miners	$4.26	1	$0.34		$4.60
Computer Case	N/A	Amazon	$43.18	1			$43.18
24VPower Supply	N/A	Amazon	$22.83	1			$22.83
						Total:	**$4,690.98**

Appendix F – FMEA

Table 14. Failure Mode and Effects Analysis (FMEA).

Potential
Failure Mode and Effect Analysis
(Design FMEA)

_X_ System	Wingtip Vibration Simulator		FMEA Number:	1
___ Subsystem				
___ Component		Design Responsibility: Nick, Steven, Eugene	Page 1 of 1	
Product Model:	Der Vibrën Mk I	Key Date:	Prepared By:	Nick
Core Team:	Dynamica		FMEA Date (Orig.)	3/11/2014

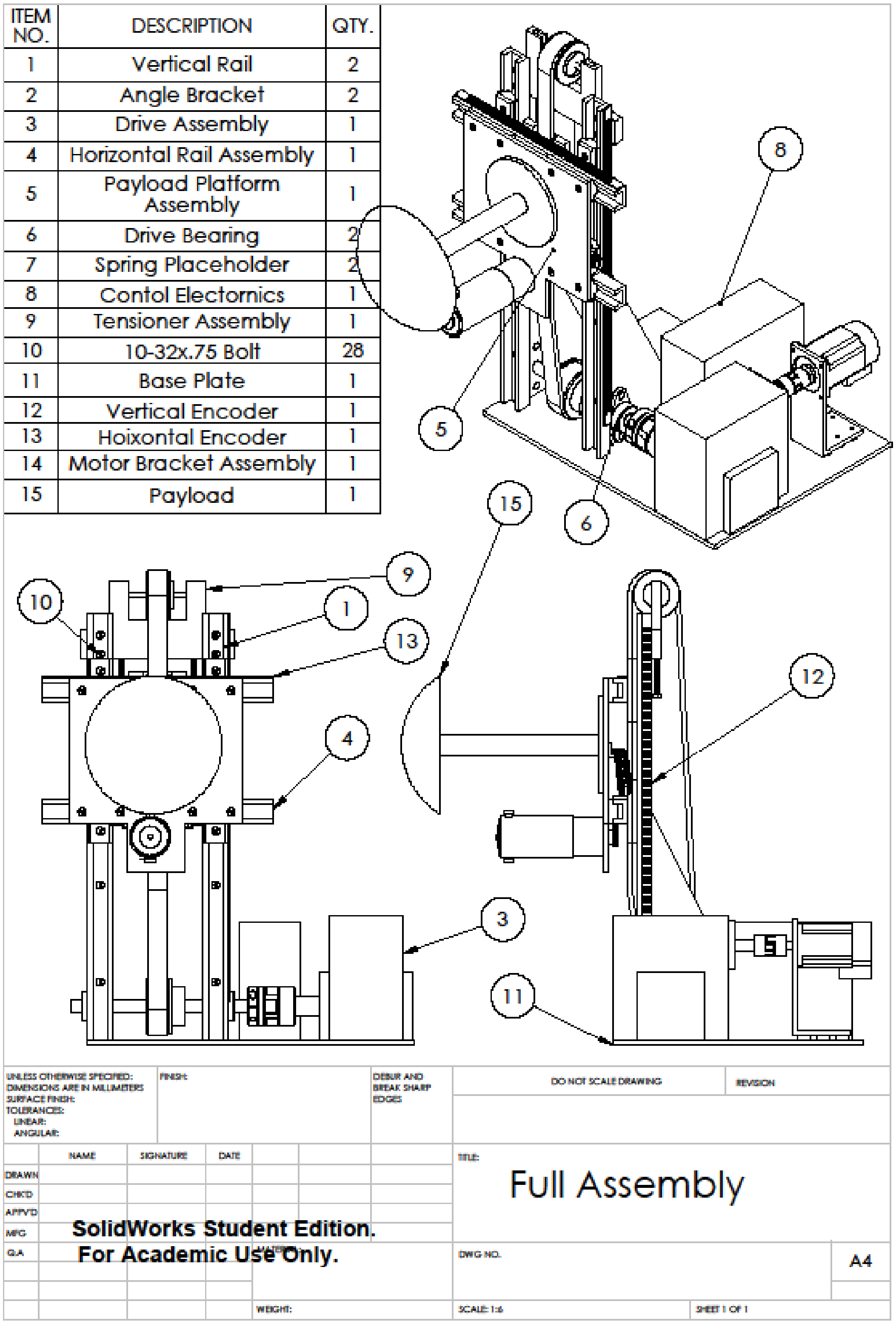
Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Sev	Action Results: Occur	Action Results: Crit
Motors must move payload vertically 11" and horizontally 1.1" peak to peak.	Motor jams	Payload motion stops	7	Environmental Factors	3	21	Instruct to operate in an anechoic chamber which is clean	Eugene - November				
				Too large of a moment on carriage	6	42	Design system to compensate for moment through support rails or counterweight	Steven - June	System is designed with factor of safety of 13 for carriage loading			
				Overloaded system	7	49	Add warning labels for maximum load capacity	Nick - November				
	Payload bottoms out	Payload hits the rail extremities	7	Input incorrect profile	6	42	Design 4 standard profiles to be used for device that will be safe	Eugene - September				
					6	42	Design crash stops at ends of rails	Steven-June				
				Random amplitudes traveling further than expected	4	28	Add 2" safety distance on track	Nick - June	Designed tracks to include extra distance			
				Power outage during operation	1	7	Put failsafe brake in system	Steven - September	Worm gear and spring system prevent overshoot during loss of power			
				Belt clip fails	1	7	Ensure belt clip is installed correctly during assembly	Eugene- September				
	Motor burns out	Need to replace expensive motor	10	Device jams	3	30	Incorporate fuse into system and observe for jams while in motion	Nick-May				
				Drive supplies higher current than motor is rated for	1	10	Select drive with maximum power output lower than motor's power rating	Steven-May	Drive can output 400W while motor is rated for 440W			
	Electroncs overheat	System wll stop working	8	Lack of airflow/coolant to electronics	5	40	Incorporate cooling system or fan into any enclosed areas with electronics	Eugene-May				
Need real time knowledge of system	Receive incorrect data	Need to re perform tests	5	Encoders lose position	3	15	Calbrate encoders correctly before use and ensure ther readings are accurate	Operator				
			5	Feedback cables damaged	1	5	Inspect cables and connectors before use	Operator				
Frame must stabilize the system with a 10lb payload attached and in motion.	Frame experiences fatigue	The frame is cracked	7	Weld Joint Fatigue	4	28	Stress analysis on structure to ensure max stress on joint is safe	Eugene - June	Frame designed with large factor of safety to prevent failure			
	Frame is corroded	The frame is rusted	3	Scratches or chips on paint, exposing metal	2	0	Instructions on how to inspect and maintain paint surface integrety	Nick - November				
Track interface allows for smooth motion and restrains the payload to two axis (Z-vertical and X-Horizontal)	Track interface jams preventing payload motion	Track is jamming the payload motion	7	Too large of torque for anti friction device	4	0	Design a rail system that can handle 1.5x possible torque	Steven - June	Ral system has factory of safety larger than 1.5			
				Environmental Factors	3	0	Instruct to operate in an anechoic chamber which is clean	Eugene - June				
				Not enough lubrication	4	0	Select low friction devices that can work	Nick - June	Bearings do not need to be lubricated,			

Appendix G – Design Verification Plan

Table 15. Design Verification Plan (DVP)

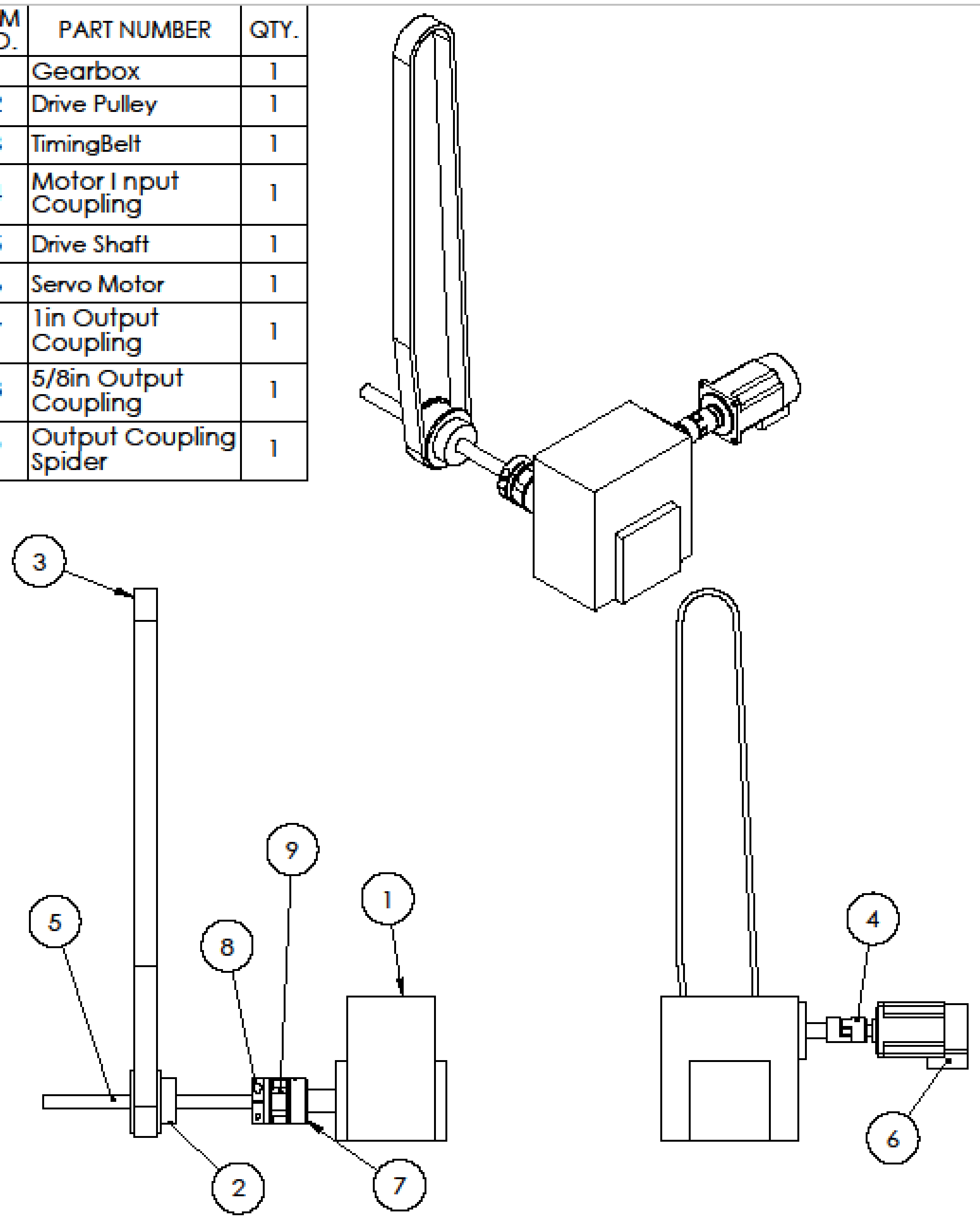
Report Date		3/11/2014	Sponsor	Raytheon					Component/Assembly			REPORTING ENGINEER:	
TEST PLAN										TEST REPORT			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES Quantity	SAMPLES Type	TIMING Start date	TIMING Finish date	TEST RESULTS Test Result	TEST RESULTS Quantity Pass	TEST RESULTS Quantity Fail	NOTES
1	Verify positional control (Vertical)	Define user units for Kinetix drive and verify that system is moving to specified positions within acceptable tolerances	±0.050"	Nick	PV	10	C	10/14/2014	11/1/2014	Accuracy within 1/16"	10	0	
2	Verify positional control (Horizontal)	Verify the control system's capability of specifying and meeting an output position through proportional control using a potentiometer	±0.050"	Eugene	PV	10	C	10/14/2014	11/1/2014	Accuracy within 0.005"	10	0	
3	Verify system can achieve specified amplitudes at appropriate frequencies (Vertical)	Create motion profile for each required mode. Run device measuring displacement and frequency. Verify that it meets or exceeds requirements	Greater than 90% of desired frequency at specified displacements	Nick	PV	10	C	11/1/2014	11/8/2014	Exceeds requirements for low amplitude. Achieves 90% for high amplitudes.	10	0	
4	Verify system can achieve specified amplitudes at appropriate frequencies (Horizontal)	Create motion profile for each required mode. Run device measuring displacement and frequency. Verify that it meets or exceeds requirements	Greater than 90% of desired frequency at specified displacements	Eugene	PV	10	C	11/1/2014	11/8/2014	Exceeds requirements for both low and high amplitudes.	10	0	
5	Verify system can generate pseudo-random motion	Create motion profile with mix of high and low amplitude peaks for both axes	Pass/Fail	Steven	PV	10	C	11/8/2014	#########	System generated suitable motion profiles in both axes	10	0	

Appendix H – Detailed Drawings



ITEM NO.	DESCRIPTION	QTY.
1	Vertical Rail	2
2	Angle Bracket	2
3	Drive Assembly	1
4	Horizontal Rail Assembly	1
5	Payload Platform Assembly	1
6	Drive Bearing	2
7	Spring Placeholder	2
8	Contol Electronics	1
9	Tensioner Assembly	1
10	10-32x.75 Bolt	28
11	Base Plate	1
12	Vertical Encoder	1
13	Hoixontal Encoder	1
14	Motor Bracket Assembly	1
15	Payload	1

ITEM NO.	PART NUMBER	QTY.
1	Gearbox	1
2	Drive Pulley	1
3	TimingBelt	1
4	Motor I nput Coupling	1
5	Drive Shaft	1
6	Servo Motor	1
7	1in Output Coupling	1
8	5/8in Output Coupling	1
9	Output Coupling Spider	1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

Drive Assembly

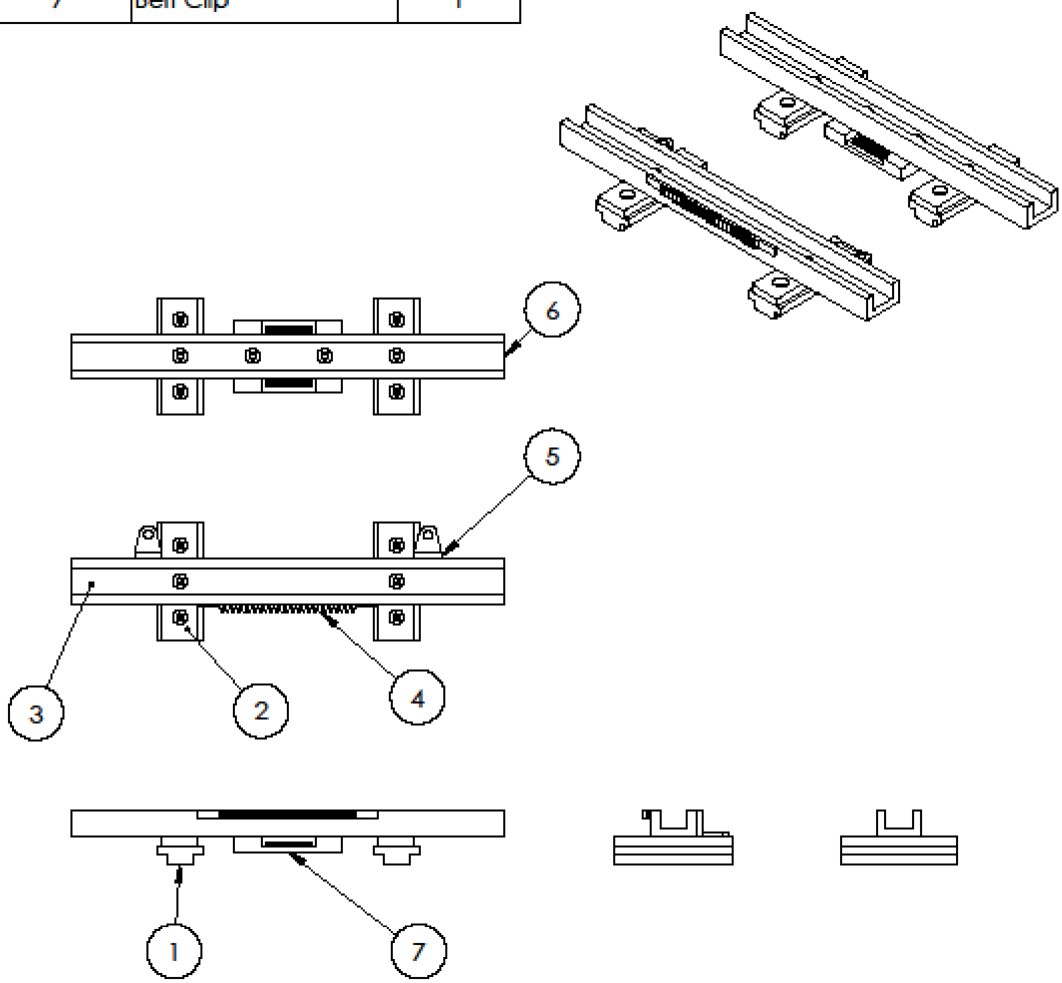
DWG NO. Drive Assembly

A4

SCALE:1:10

SHEET 1 OF 1

ITEM NO.	PART NUMBER	QTY.
1	Carriage	4
2	Carriage Bracket	4
3	Rail Short	1
4	Rack	1
5	Spring Loop A	2
6	Rail Short Top	1
7	Belt Clip	1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Horizontal Rail Assembly

MATERIAL:

WEIGHT:

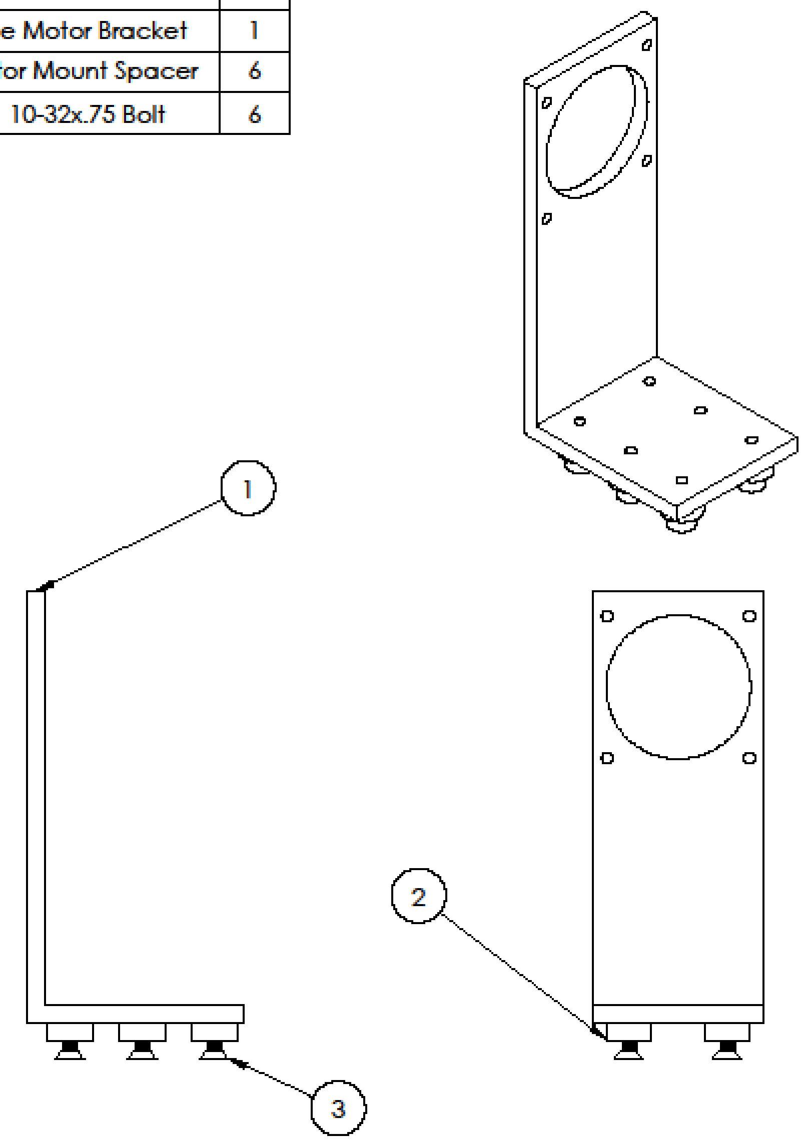
DWG NO.

A4

SCALE: 1:4

SHEET 1 OF 1

ITEM NO.	Description	QTY.
1	Drive Motor Bracket	1
2	Motor Mount Spacer	6
3	10-32x.75 Bolt	6



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

Motor Bracket Assembly

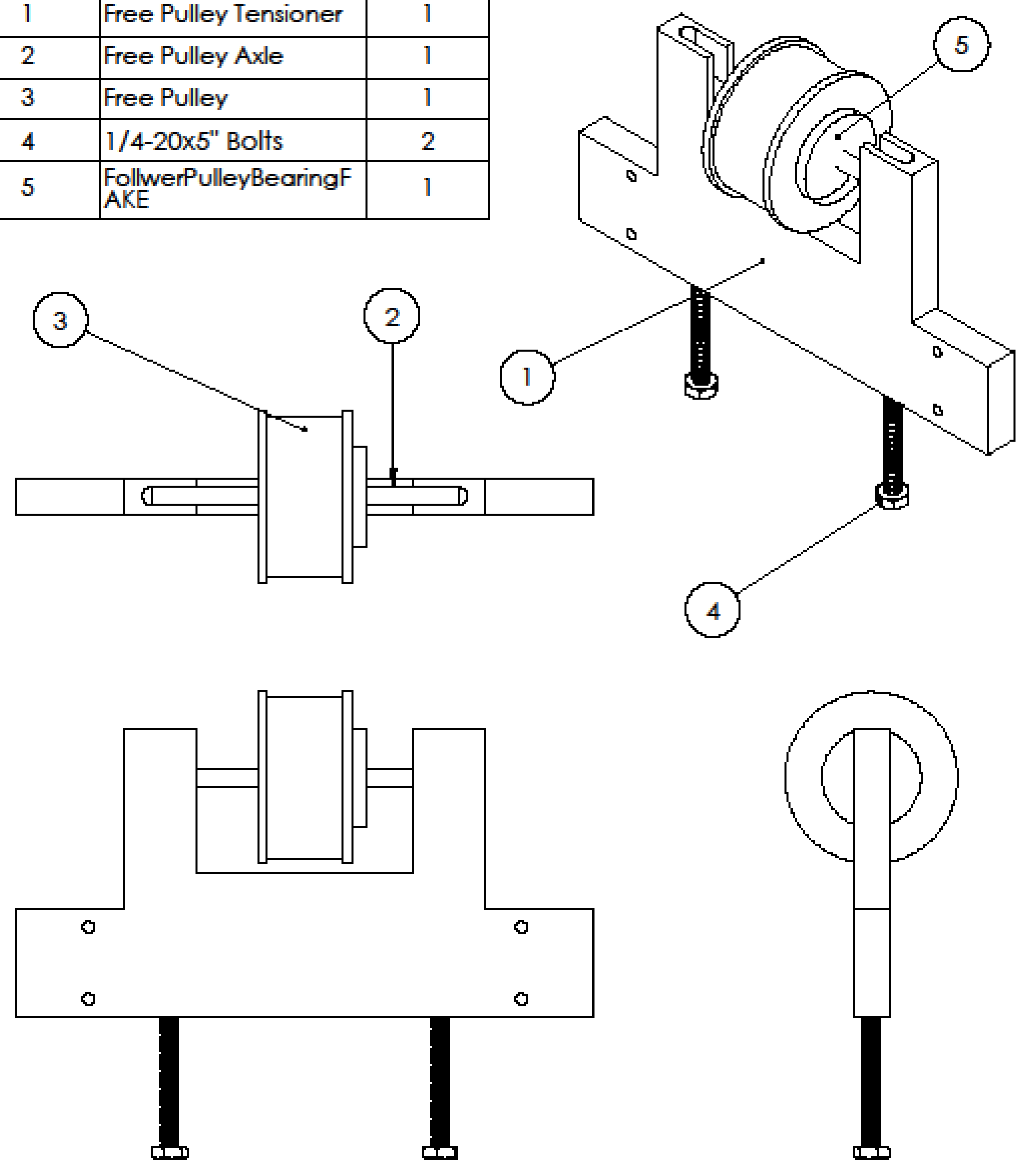
DWG NO.

A4

SCALE:1:2

SHEET 1 OF 1

ITEM NO.	PART NUMBER	QTY.
1	Free Pulley Tensioner	1
2	Free Pulley Axle	1
3	Free Pulley	1
4	1/4-20x5" Bolts	2
5	FollwerPulleyBearingFAKE	1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

Tensioner Assembly

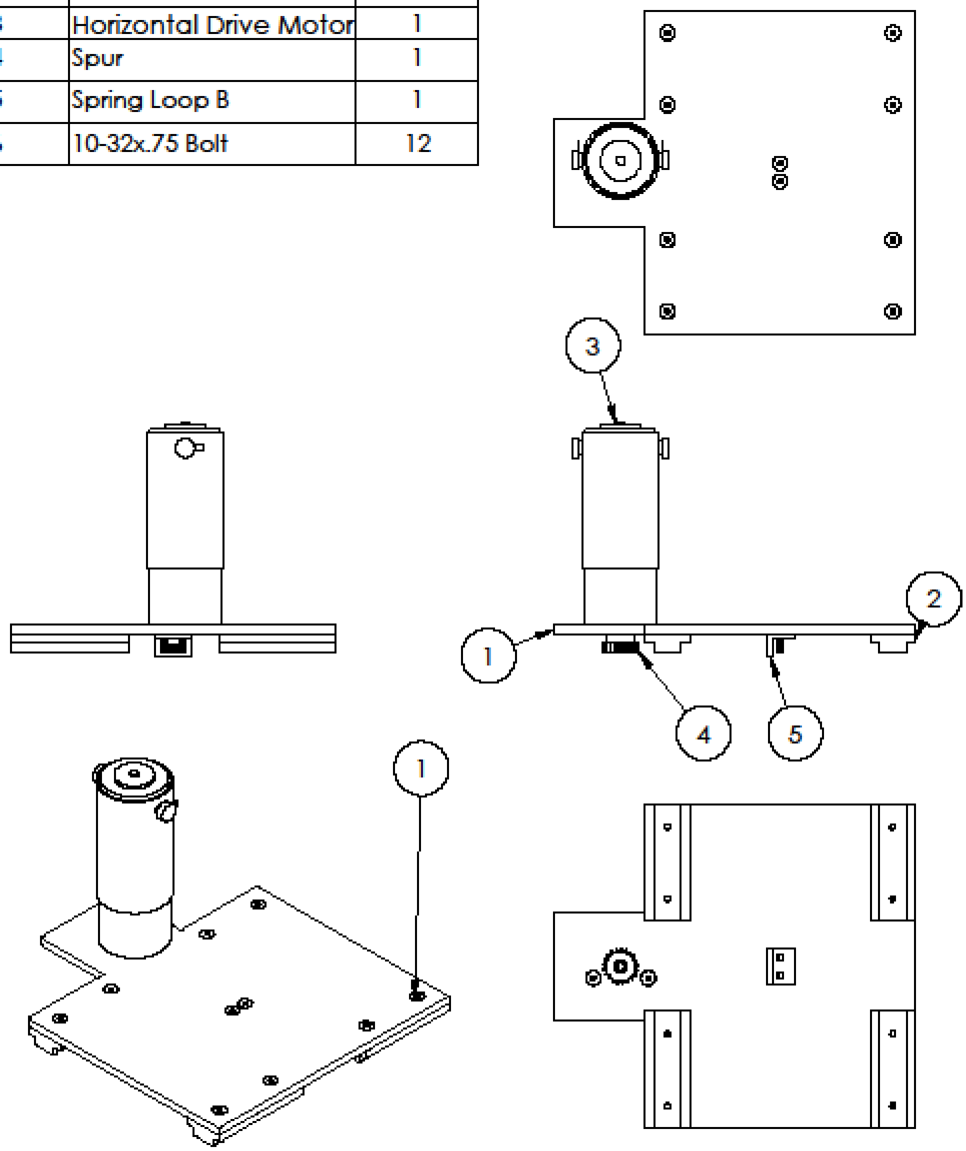
DWG NO.

A4

SCALE: 1:2

SHEET 1 OF 1

ITEM NO.	PART NUMBER	QTY.
1	Payload Plate	1
2	Carriage	4
3	Horizontal Drive Motor	1
4	Spur	1
5	Spring Loop B	1
6	10-32x.75 Bolt	12



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Payload Platform Assembly

MATERIAL:

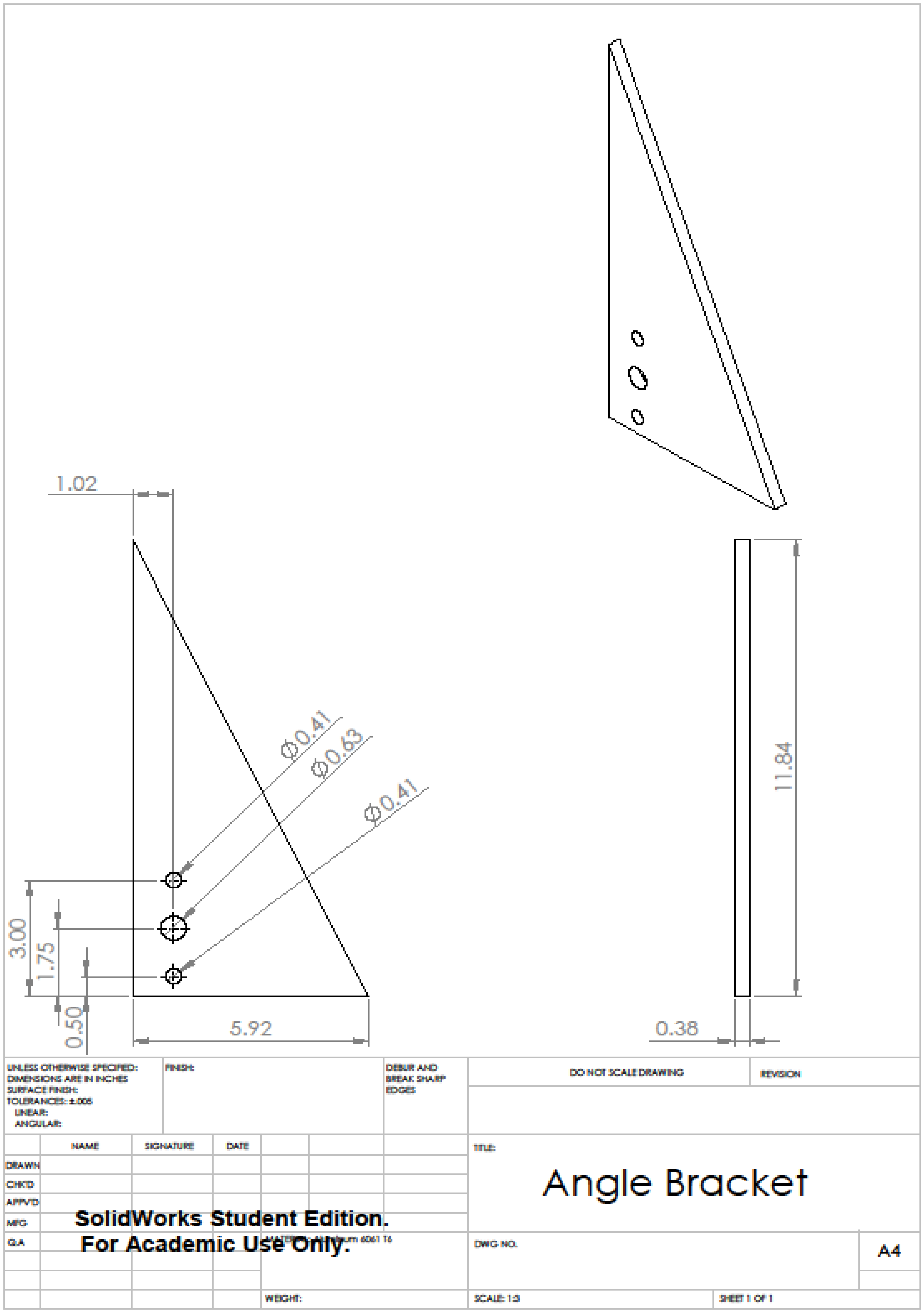
DWG NO.

A4

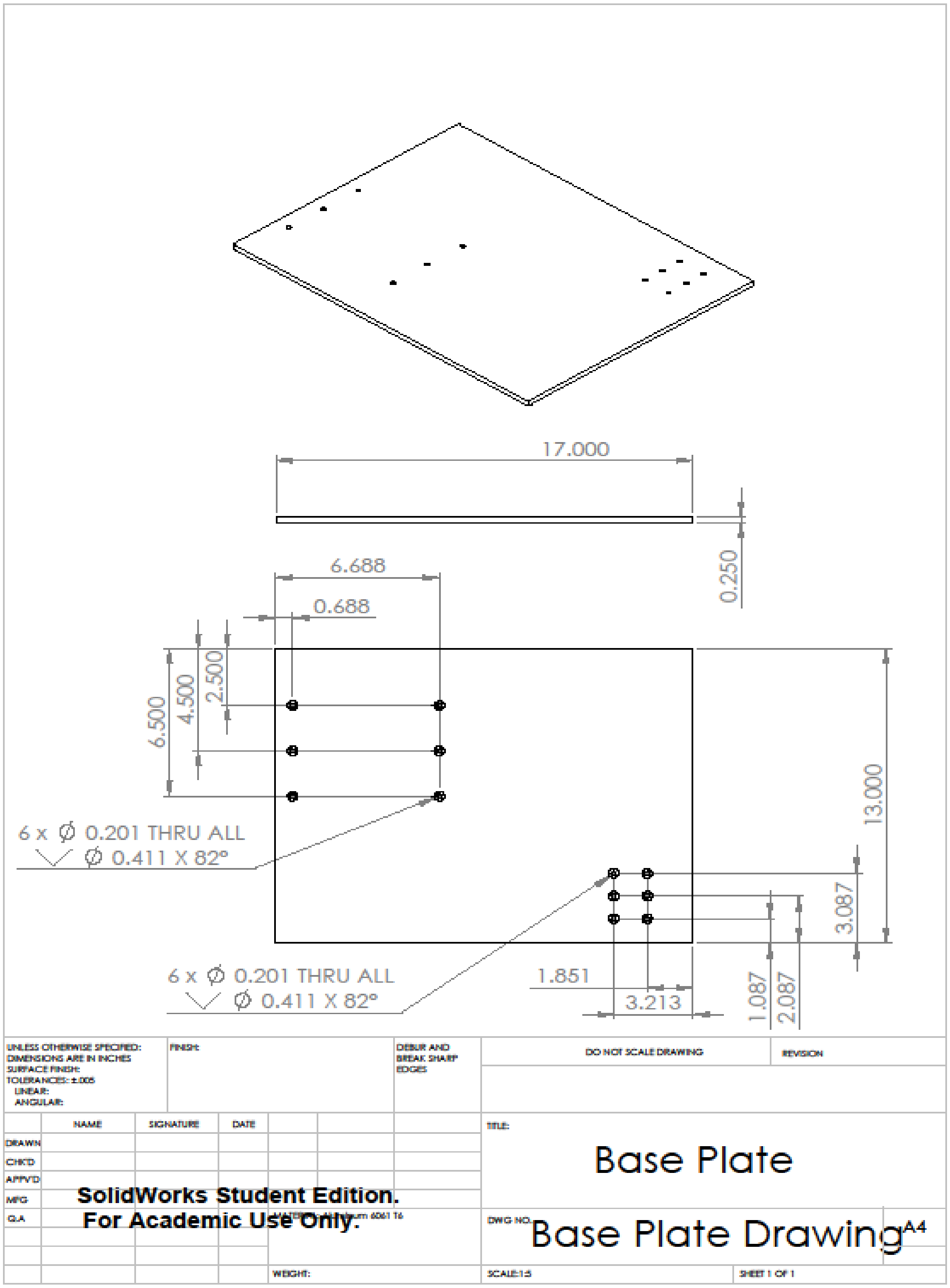
WEIGHT:

SCALE: 1:4

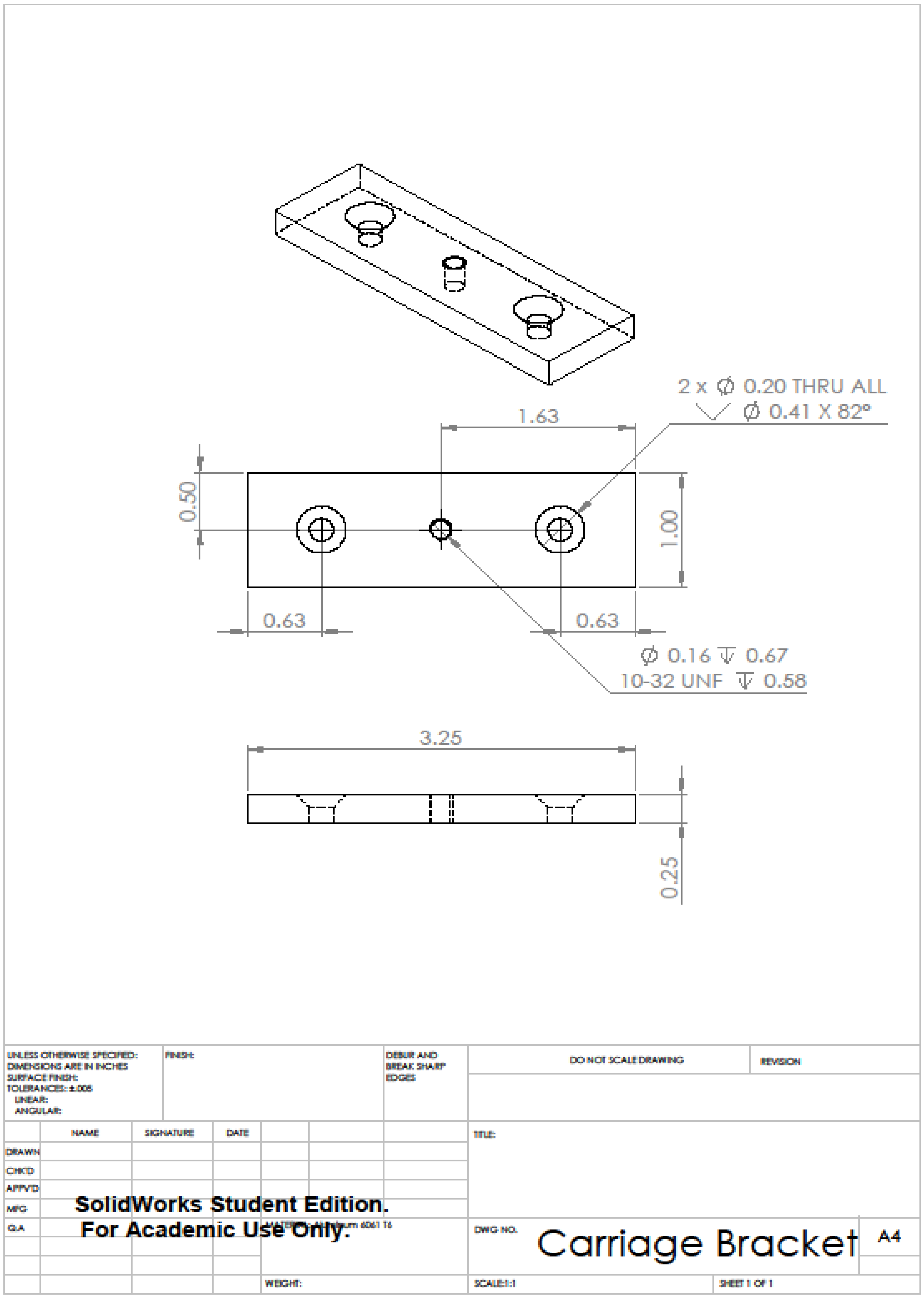
SHEET 1 OF 1



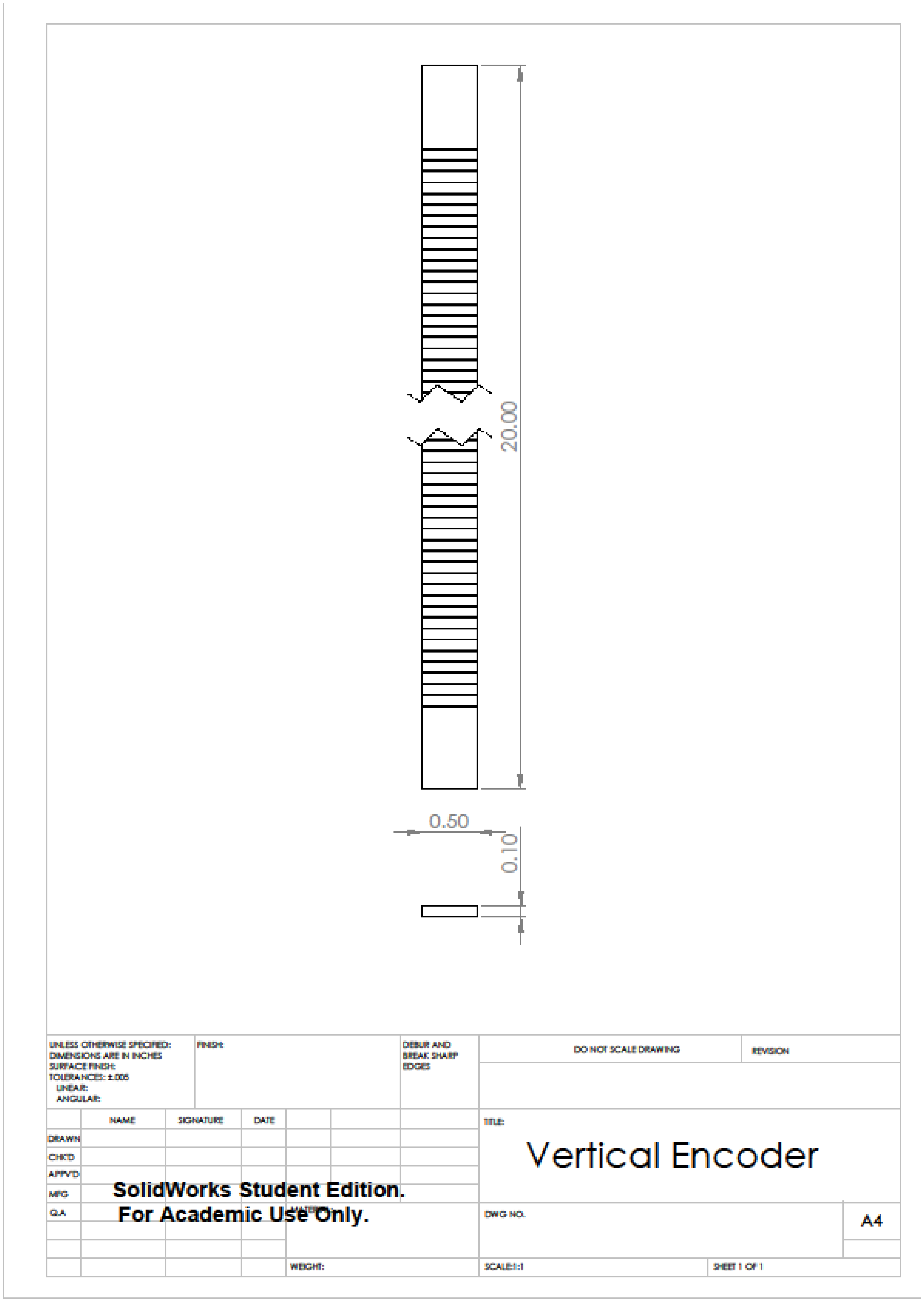
Note: The Angle Brackets will be cut from one large plate of aluminum. It will be cut diagonally on a band saw with a blade width of .125in, leaving two triangles for the brackets.

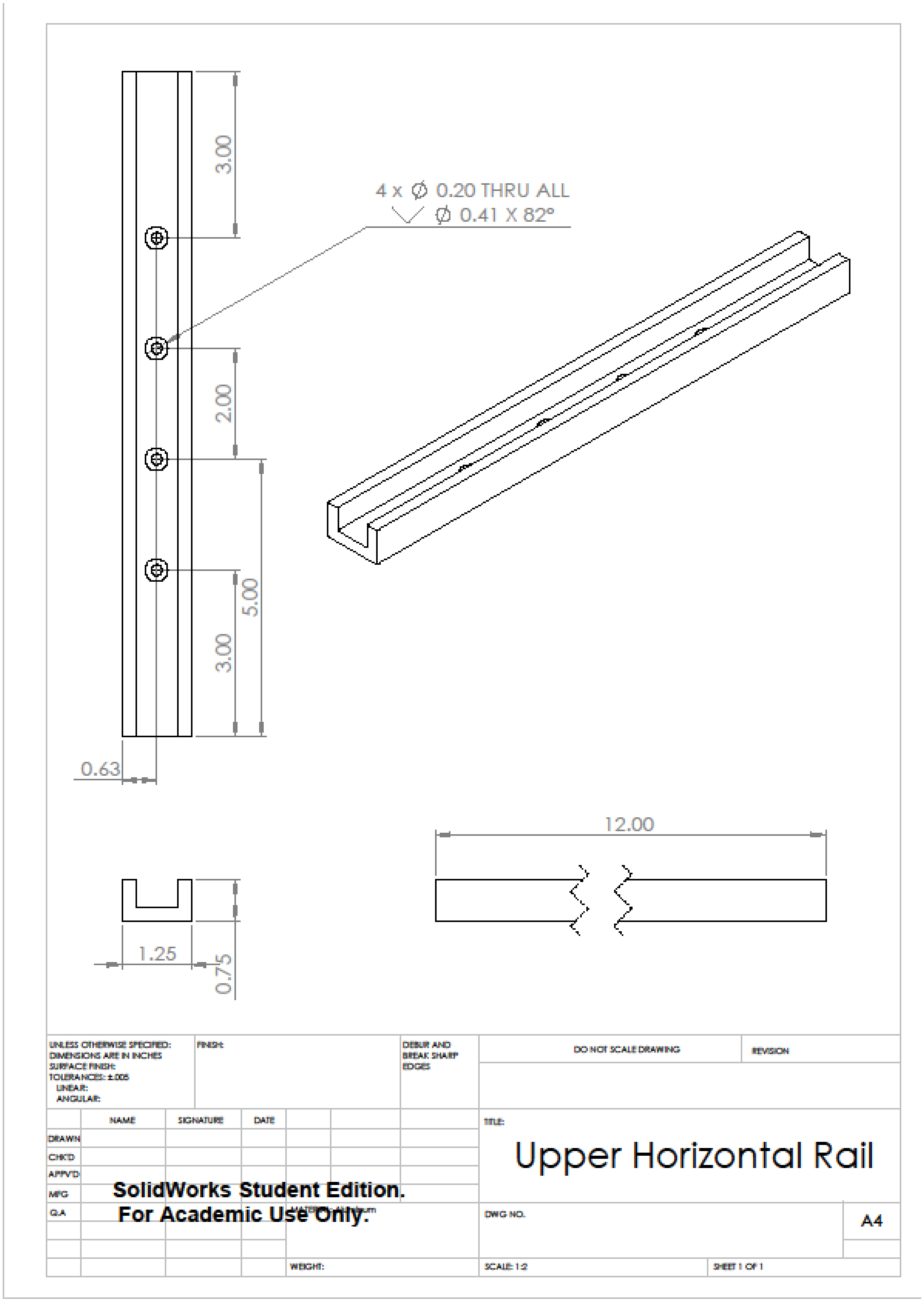


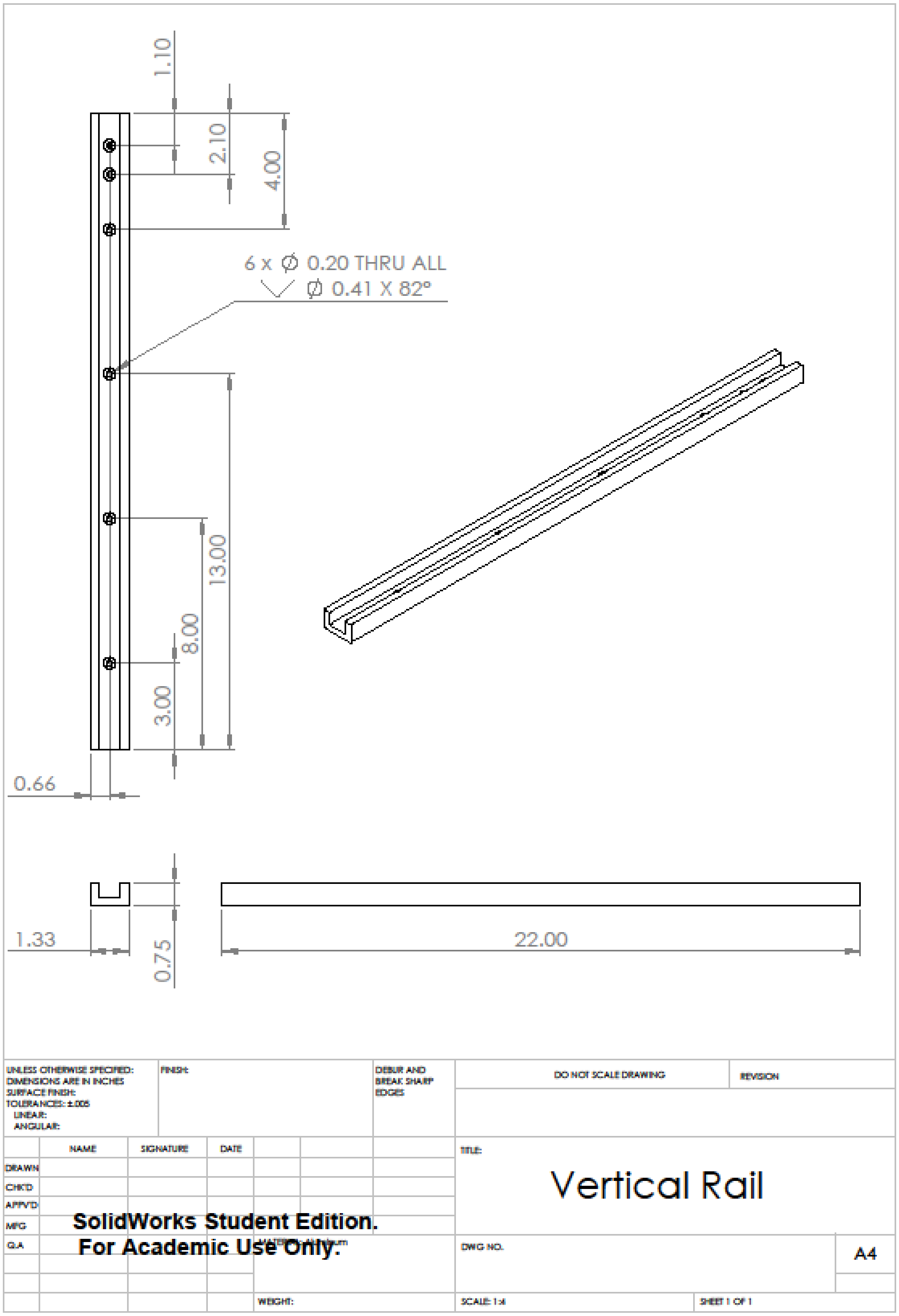
Note: If possible, all holes should be drilled in the same set up on a mill and indexed to the same location. The position of the holes relative to each other is more important than their absolute position on the plate.

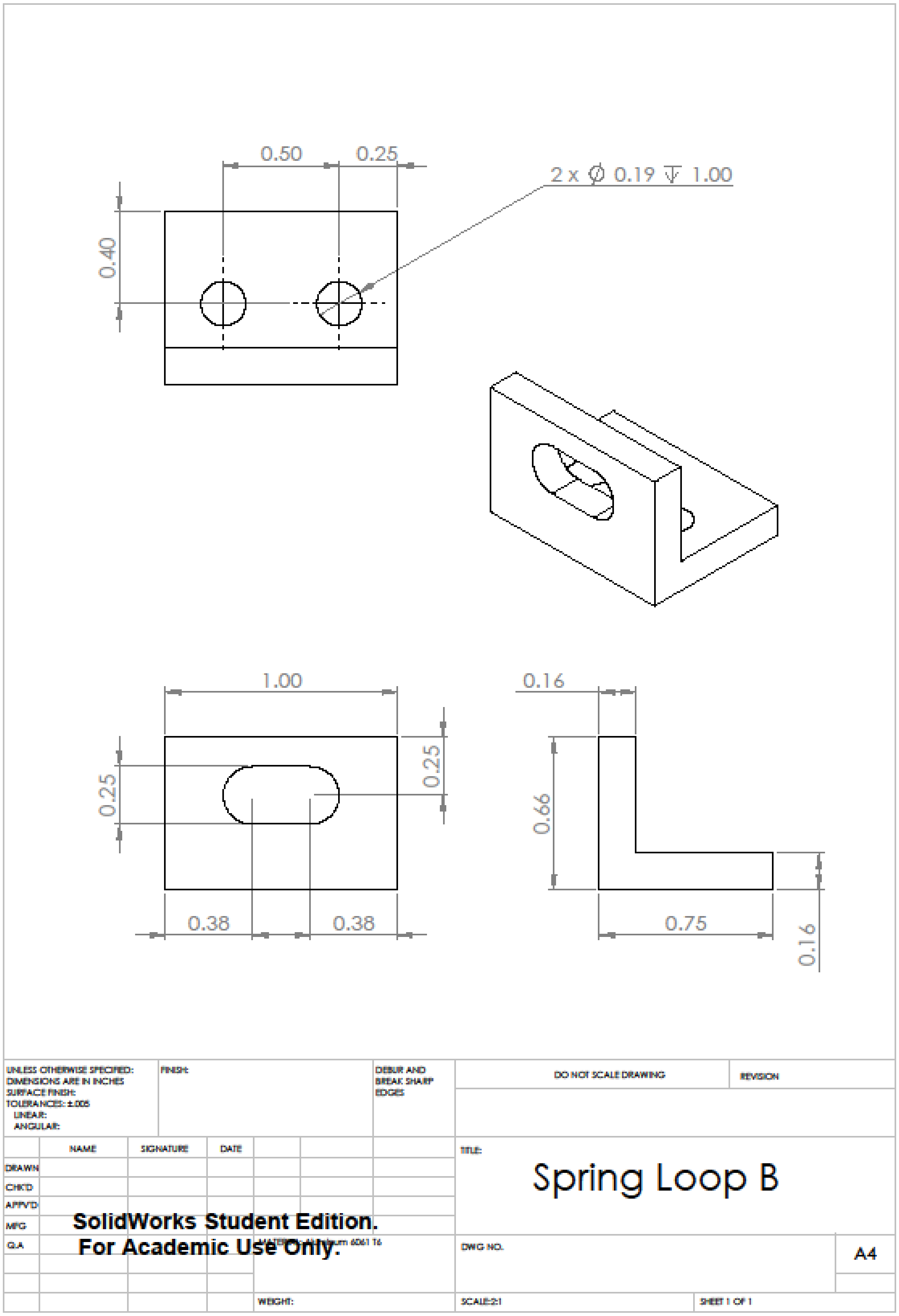


Note: This part will be made from off-fall from the base plate. No additional stock is necessary

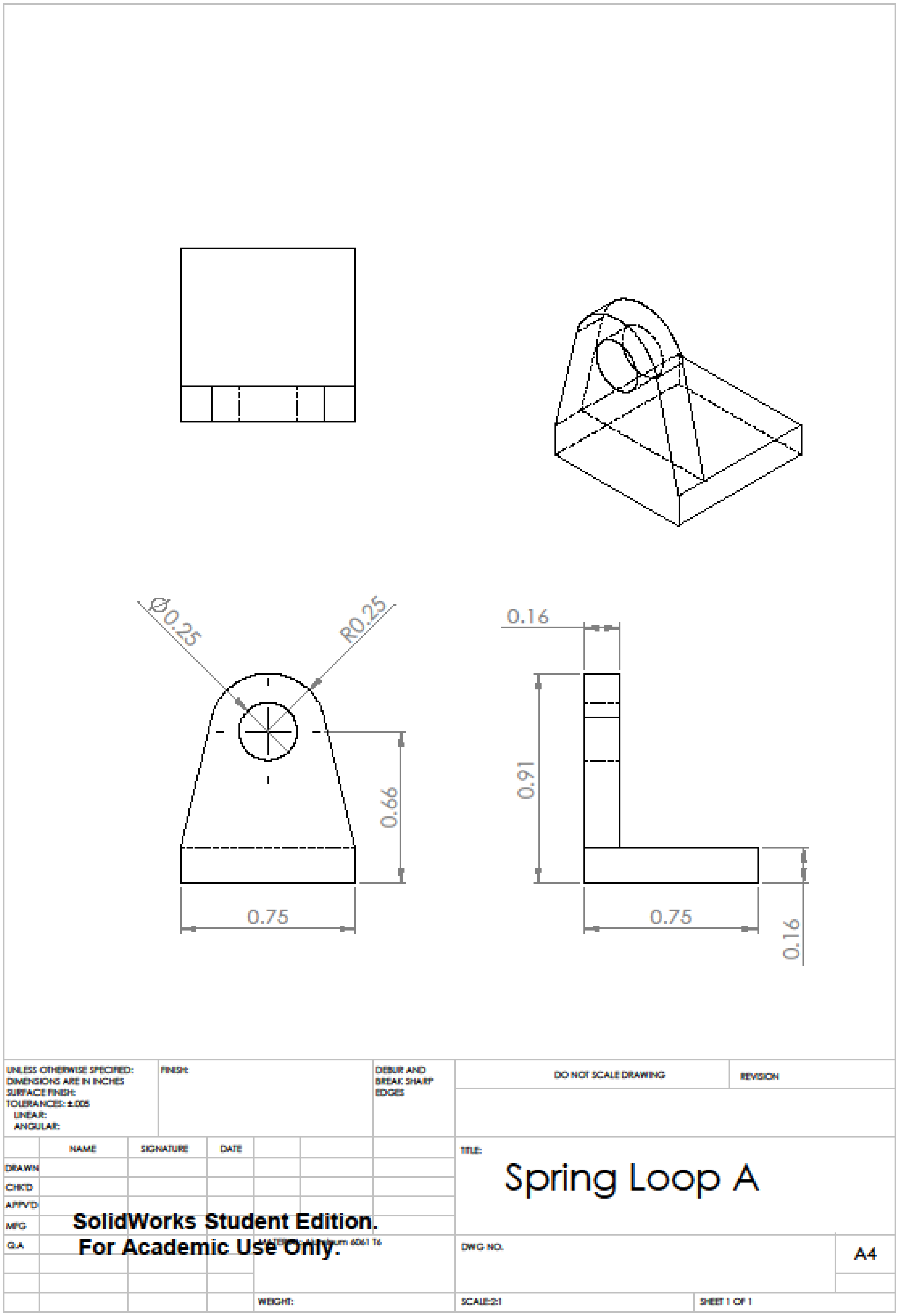

20.00
0.50
0.10
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±.005
LINEAR:
ANGULAR:
FINISH:
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
Vertical Encoder
SolidWorks Student Edition.
For Academic Use Only.
MATERIAL:
DWG NO.
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1

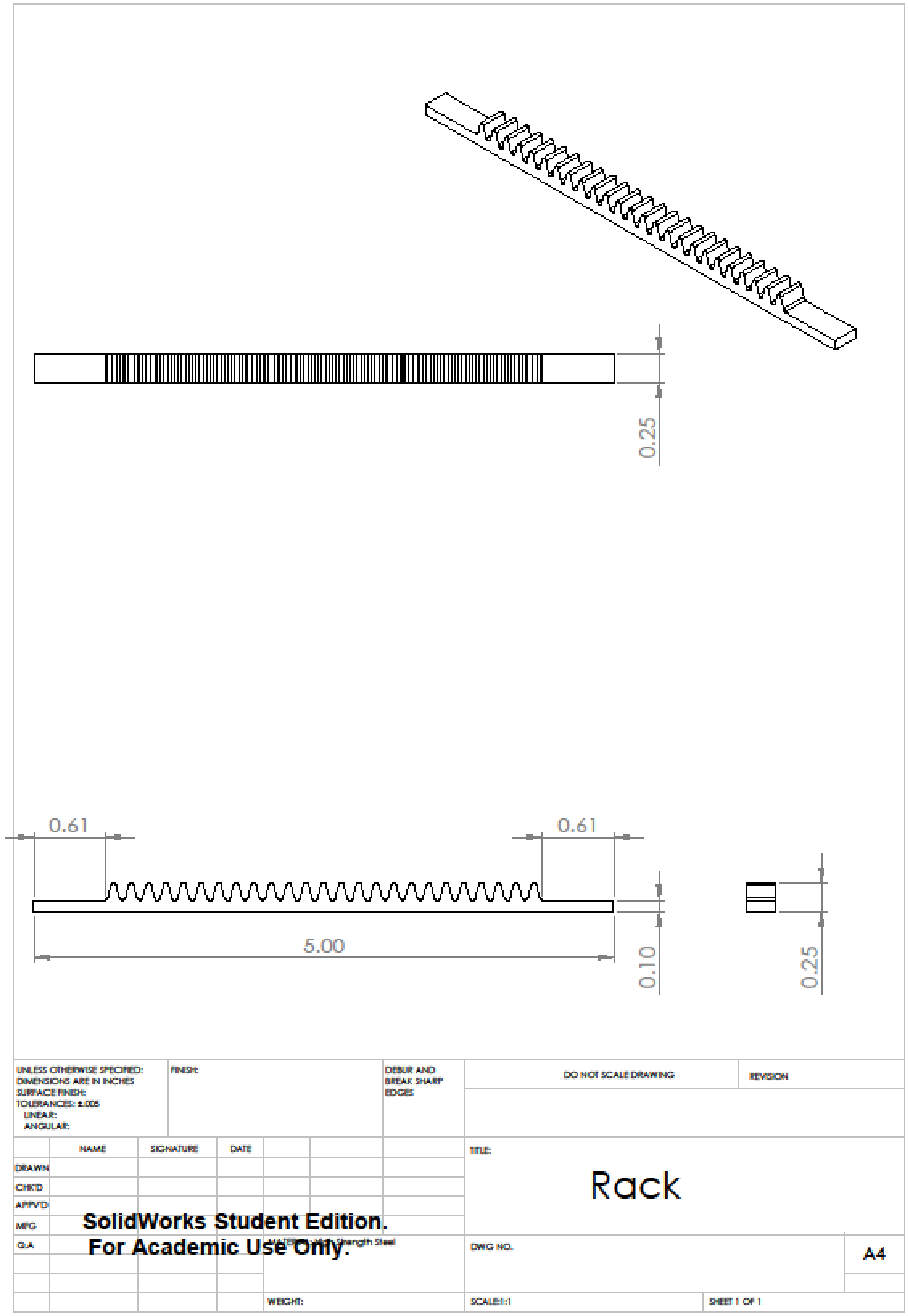

3.00
4 x Ø 0.20 THRU ALL
Ø 0.41 X 82°
2.00
5.00
3.00
0.63
12.00
1.25
0.75
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±.005
LINEAR:
ANGULAR:
FINISH:
DEBUR AND
BREAK SHARP
EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
Upper Horizontal Rail
SolidWorks Student Edition.
For Academic Use Only.
DWG NO.
A4
WEIGHT:
SCALE: 1:2
SHEET 1 OF 1

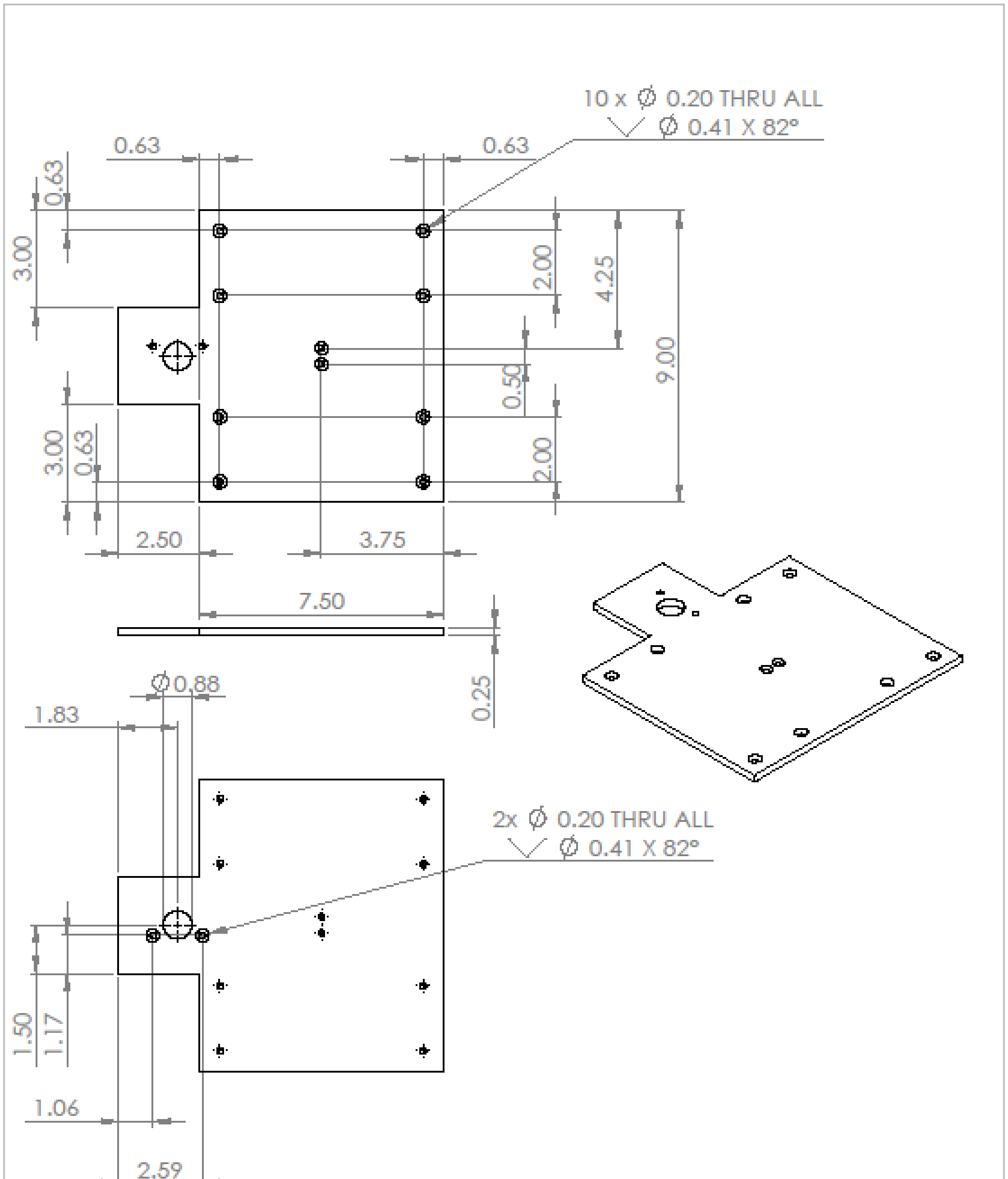

1.10
2.10
4.00
6 x Ø 0.20 THRU ALL
Ø 0.41 X 82°
13.00
8.00
3.00
0.66
1.33
0.75
22.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±.005
LINEAR:
ANGULAR:
FINISH:
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
Vertical Rail
SolidWorks Student Edition.
For Academic Use Only.
DWG NO.
A4
WEIGHT:
SCALE: 1:4
SHEET 1 OF 1



0.50
0.25
2 x ⌀ 0.19 ↧ 1.00
0.40
1.00
0.25
0.25
0.38
0.38
0.16
0.66
0.75
0.16
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±.005
LINEAR:
ANGULAR:
FINISH:
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
Spring Loop B
SolidWorks Student Edition.
For Academic Use Only.
DWG NO.
A4
WEIGHT:
SCALE:2:1
SHEET 1 OF 1


Ø0.25
R0.25
0.66
0.75
0.16
0.91
0.75
0.16
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±.005
LINEAR:
ANGULAR:
FINISH:
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
Spring Loop A
SolidWorks Student Edition.
For Academic Use Only.
DWG NO.
A4
WEIGHT:
SCALE:2:1
SHEET 1 OF 1


0.25
0.61
0.61
5.00
0.10
0.25
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±.005
LINEAR:
ANGULAR:
FINISH:
DEBUR AND
BREAK SHARP
EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
Rack
SolidWorks Student Edition.
For Academic Use Only.
DWG NO.
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±.005
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Payload Plate

MATERIAL: Carbon Fiber Composite

DWG NO.

A4

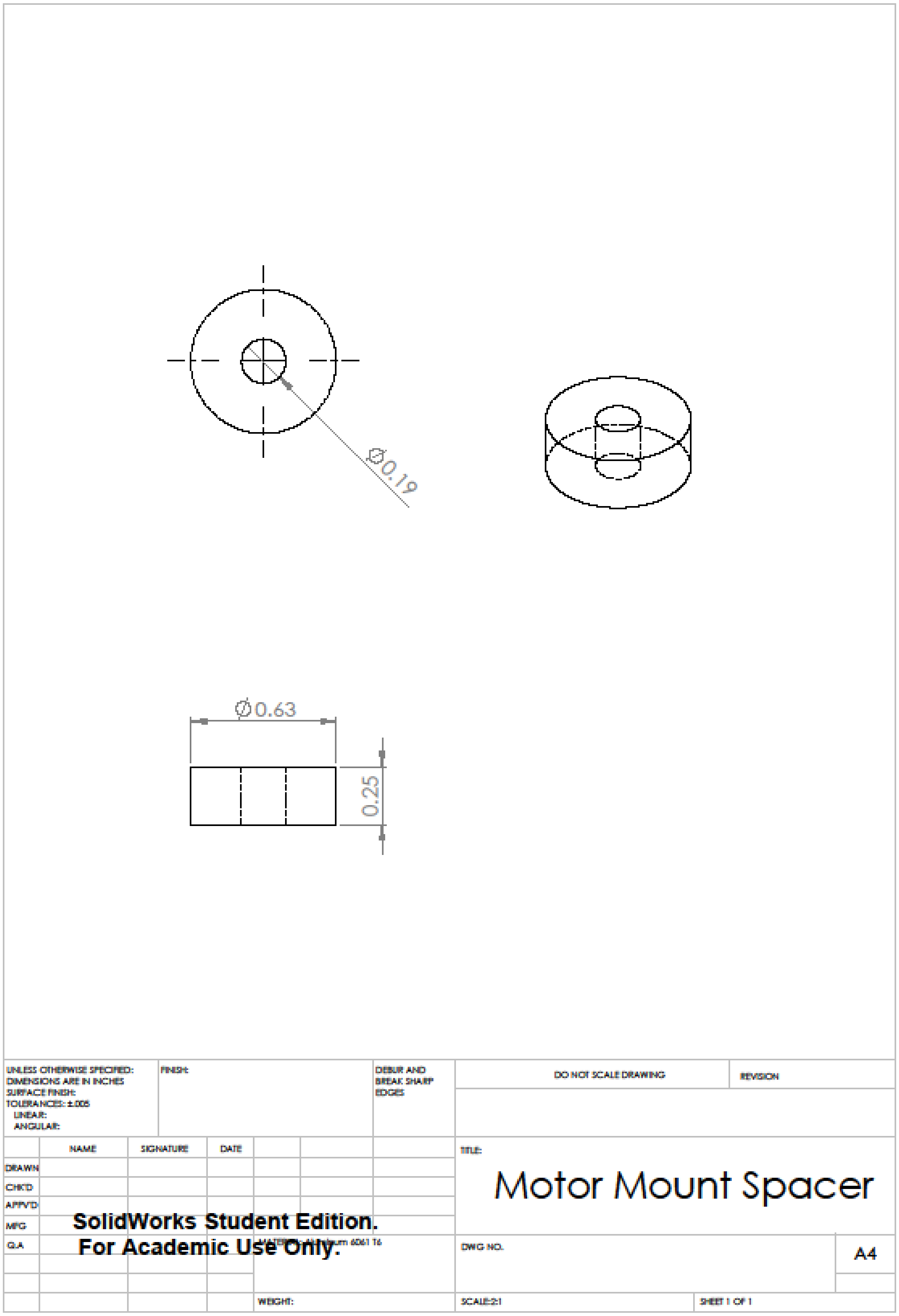
WEIGHT:

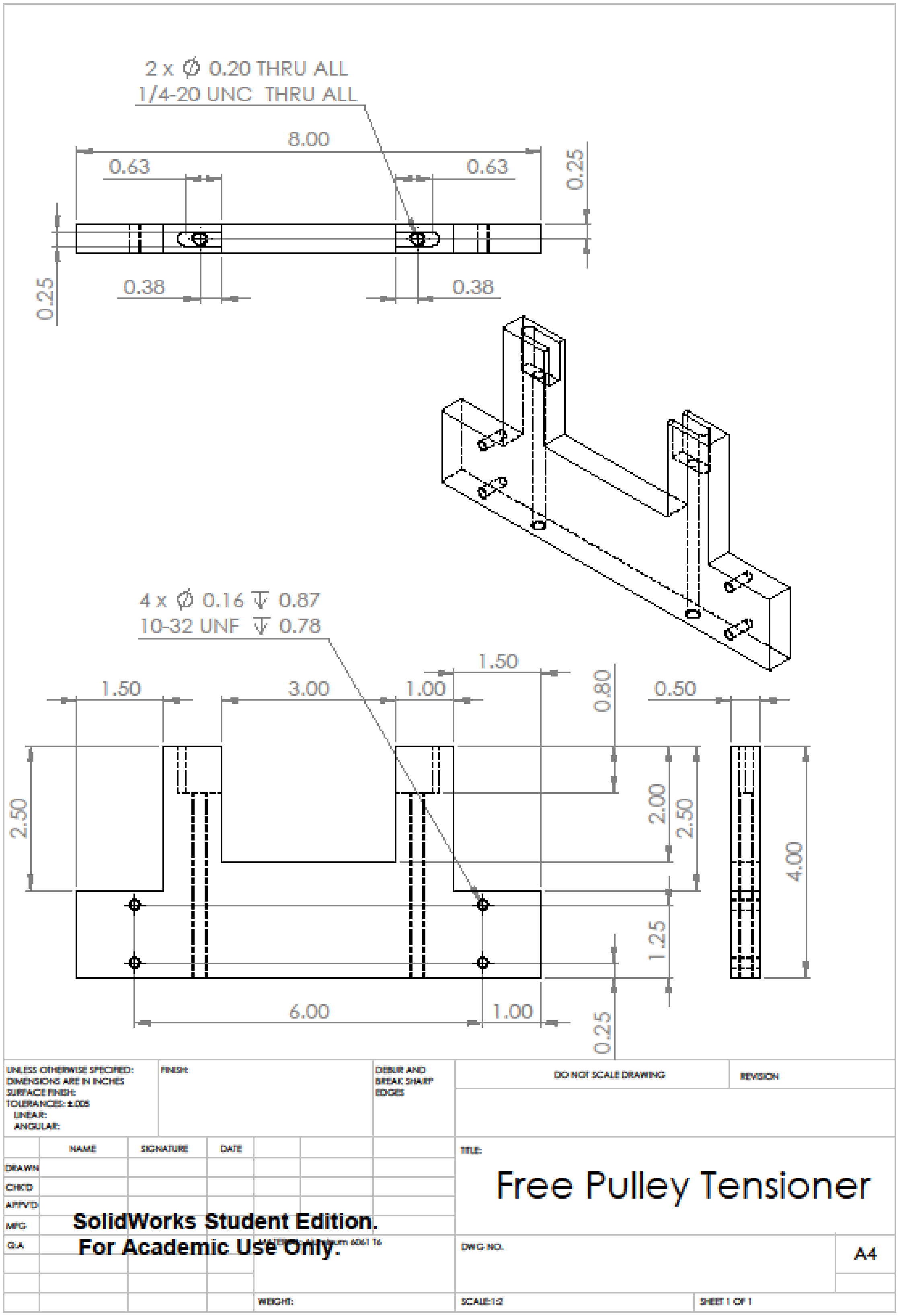
SCALE: 1:4

SHEET 1 OF 1

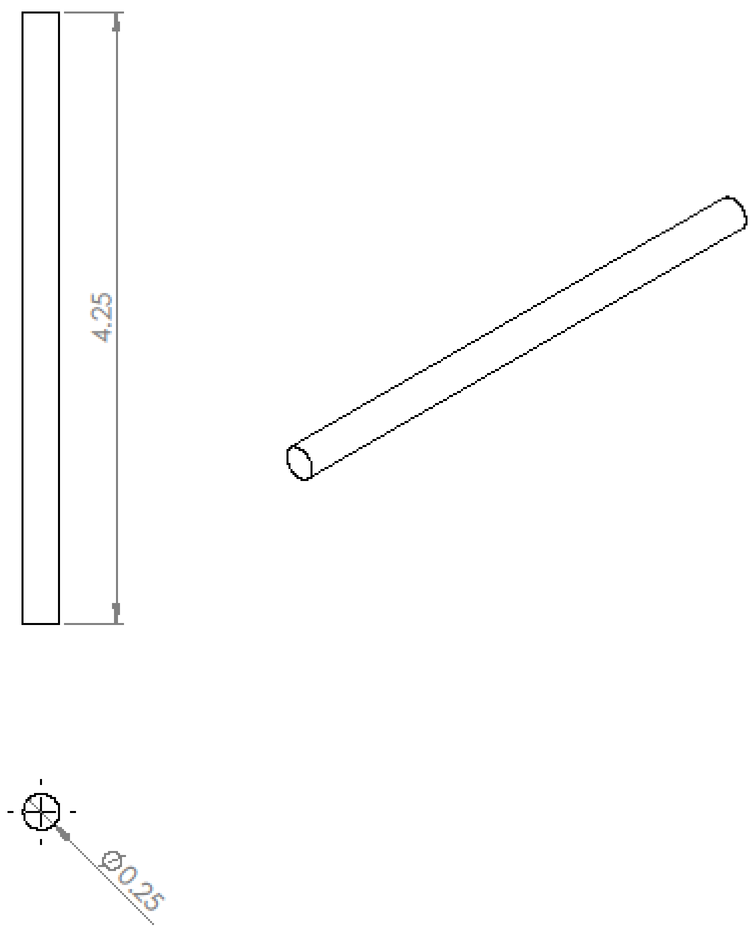
Note: This part will be made from .25in carbon fiber plate. Care must be taken during manufacture, as carbon fiber particles are harmful to people. Wear gloves, a respirator, and clothing with long sleeves. Have a second operator standing by with a vacuum to remove dust/chips as they form.

Roughing operations for the shape of the plate will be done with a band saw. Finishing cuts can be made with a mill if necessary. All holes will be drilled on a mill. Operator will index off the bottom right corner, and locate all holes relative to that location. Then the plate will be flipped over, and the operator will again index off the same corner to locate the holes that need to be countersunk from the opposite side.


Ø0.19
Ø0.63
0.25
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±.005
LINEAR:
ANGULAR:
FINISH:
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
Motor Mount Spacer
SolidWorks Student Edition.
For Academic Use Only.
DWG NO.
A4
WEIGHT:
SCALE:2:1
SHEET 1 OF 1


2 x Ø 0.20 THRU ALL
1/4-20 UNC THRU ALL
8.00
0.63
0.63
0.25
0.25
0.38
0.38
4 x Ø 0.16 ↧ 0.87
10-32 UNF ↧ 0.78
1.50
1.50
3.00
1.00
0.80
0.50
2.50
2.00
2.50
4.00
1.25
6.00
1.00
0.25
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±.005
LINEAR:
ANGULAR:
FINISH:
DEBUR AND
BREAK SHARP
EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
Free Pulley Tensioner
SolidWorks Student Edition.
For Academic Use Only.
DWG NO.
A4
WEIGHT:
SCALE:1:2
SHEET 1 OF 1

Note: Roughing cuts for this part should be made on a band saw, with care taken not to remove too much material. Finishing passes will be made on a mill. Interior corners do not need to be square, with radii allowable up to .5in at the machinists discretion. If the long tapped holes cannot be tapped fully, it is acceptable to drill them as clearance holes up until .75in from the top of the part. The remaining area should be tapped.



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±.005
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: Aluminum 6061 T6

WEIGHT:

TITLE:

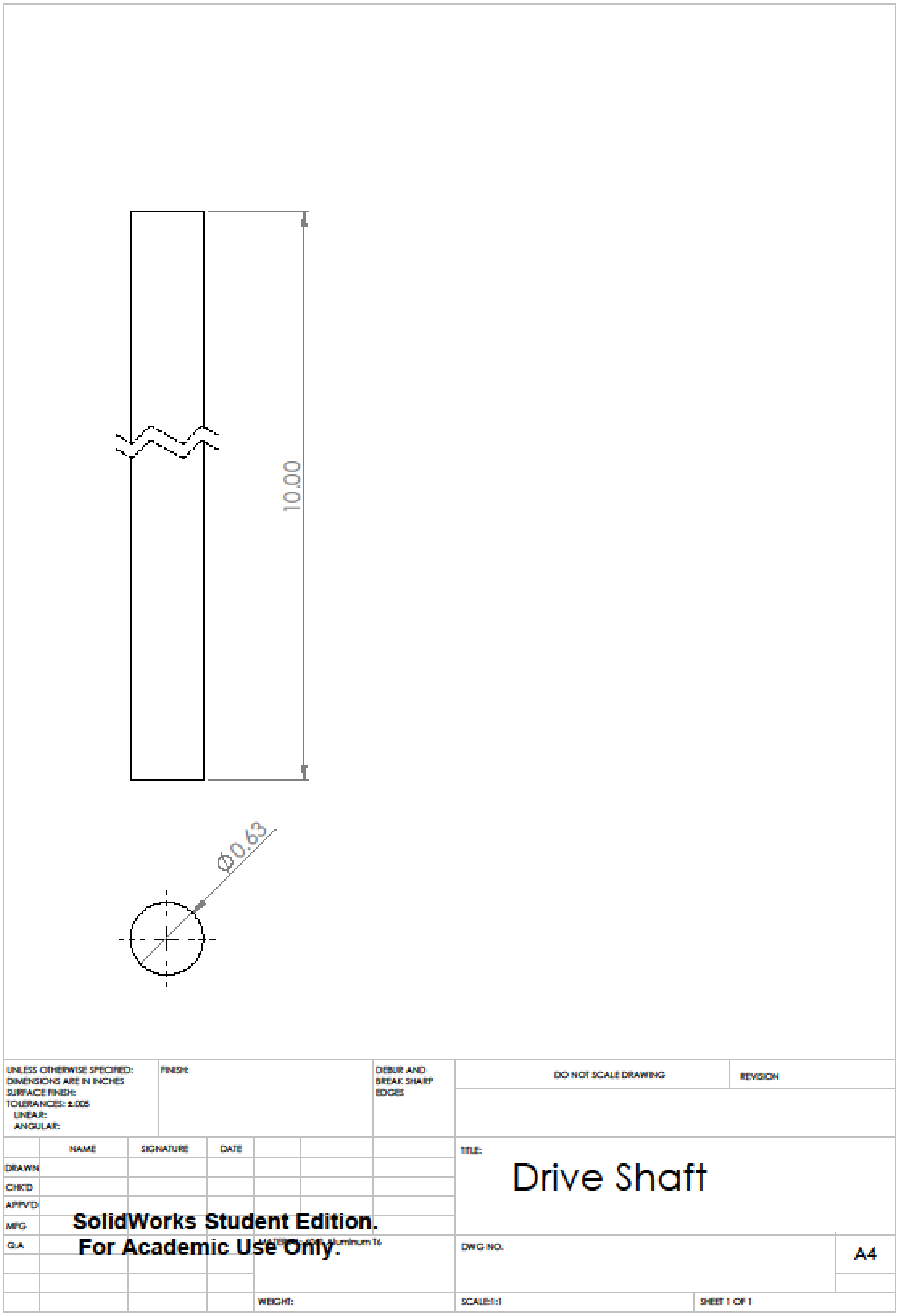
Free Pulley Axle

DWG NO.

A4

SCALE:1:1

SHEET 1 OF 1



10.00
Ø0.63
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±.005
LINEAR:
ANGULAR:
FINISH:
DEBUR AND
BREAK SHARP
EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
Drive Shaft
SolidWorks Student Edition.
For Academic Use Only.
DWG NO.
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1

Appendix I – HorizontalMotion Arduino Code

```
/*========================================
 Horizontal Axis Controller
 Parts required:
 Pololu VNH5019 Motor Driver Carrier
 Pittman 12V DC Motor

 Created 20 November 2014
 by Eugene Fox
 foxeugenef@gmail.com

This code must me in a file called "HorizontalMotion.ino" and be put in a folder called
                                        "HorizontalMotion" to work with the Arduino IDE
 ========================================*/

/*========================================
Configuration parameters
========================================*/
const int peakOccurPercent = 10;          // "Percent occurence of peak motion" Percent of how likely the high amplitide stroke should occur.
const int midOccurPercent = 10;           // "Percent occurence of mid range motion" Percent of how likely the intermediate motion should occur.
const int noAmplitudePercent = 15;        // "Percent occurence of very small motion" Practically motionless for an instant.
const int smallOccurPercent = 65;         // (unused variable)"Percent occurence of the small motion. The sum of these should be kept at 100%.

const int rangeLimit = 600;               // outer bounds limit in 1000ths of inch. Default 600. Suggested maximum 850. Absolute max of 1000 dictated by the potentiometer stroke length.
const float Kp = .43;                     // "Proportional Gain" Suggested minum of 0.43. Increase in small inciments until satisfactory motor response. Response is also limited by maxPwm value below.
const int maxPwm = 80;                    // "max allowed motor power" Possible values: 0~255. Suggested minimum of 80. Increase when motor is unable to accelerate load fast enough.

/*========================================
ADVANCED Configuration parameters
========================================*/
const int brakeRange = 1;                 // -/+ value when system is at the desired location to apply brake
const int overcomeSticktion = 5;          // small number to add to low PWM values so motor will overcome friction
const int motorSpinFlip = 1;              // -/+ 1 Feedback signal sign to easily flip motor direction if DC wiring is backwards. Only needed if rewiring causes feedback to be reversed
const int smallAmplitude = 268/2;         // zero to peak amplitude for small motion (0.268inch @ 6.4Hz)
```

```
const float smallFreq = 6.4;                    // frequency of small motion
const int peakAmplitude = 1040/2;                    // zero to peak amplitude for large, peak motion
                                            (1.1inch @ 3.2Hz)
const float peakFreq = 3.2;                    // frequencty of large motion

/*========================================
***DO NOT EDIT CODE BELOW***
========================================*/

//const int switchPin = 2;                    // the number of the switchPin
const int directionAPin = 9;                    // the number of the direction pin A
const int directionBPin = 10;                    // the number of the direction pin B
const int pwmPin = 3;                    // the number of the PWM pin
const int potPin = 0;                    // the number of the analog-in pin
const int ledPin = 13;                    // select the pin for the LED

const float pi = 3.1416;
const long accelConst = 223931;                    // 0.58g in 1000*in/s^2 derived from a =
                                            Amplitude*(2*pi*freq)^2. This max acceleration is used to
                                            create the intermediate motions since the max accel is the same
                                            for different frequencies
int tickState = 1;                    //
int waveState = 1;                    // indicates if wave is in large mode or small
float wavePeriod = 0.1;
float periodStart = 0.001;
int waveAmplitude = 268;
//float waveFreq = 6.4;
int maxPwmToggle = 1;                    //

//int switchState = 0;                    // variable for reading the switch's state. 0 = off, 1 = on

void setup(){                    // the setup function runs once when you press reset or
                                            power the board
  //pinMode(switchPin, INPUT);                    // initiates the switch pin as an input
   pinMode(ledPin, OUTPUT);                    // declare the ledPin as an OUTPUT
   pinMode(pwmPin, OUTPUT);                    // initiates the PWM pin as an output
  pinMode(directionAPin, OUTPUT);                    // initiates the directionBApin as output
  pinMode(directionBPin, OUTPUT);                    // initiates the directionB pin as output
  //pinMode(potPin, INPUT);                    // initiates the pot pin as input
  digitalWrite(directionAPin, LOW);                    // brake to GND
  digitalWrite(directionBPin, LOW);                    // brake to GND
  digitalWrite(ledPin, LOW);                    // turn the ledPin off
  randomSeed(787);
  delay(2000);                    // wait for 2 seconds
}

/////////////////////////// the loop function runs over and over again forever as long as board is getting
                                            power
void loop(){
  //int desiredPos = positionGeneration(tickState);
```

```
  int desiredPos = posRandGen(tickState);
  int currentPos = getPos();
  int error = desiredPos - currentPos;                    // error amount in 1000ths of an inch;
  if (!posSafeLimitOk(currentPos)){
    setMotorVelocity(0);;                                 // if position is outside the safe limit, it will freeze the
                                                  motion.
  } else {
    setMotorVelocity(error*Kp);                           // P-controller gain
  }
  tickState = tickState++;
  if(tickState > 750) tickState=-750;                     // 600 = 4Hz
} // end of loop()



/////////////////////////// returns a sin wave position according to clock
int posSinGen(int tick){
  float secTime = millis()/1000.0;
  return smallAmplitude*sin(2*pi*peakFreq*secTime);
}

/////////////////////////// returns the next position. A simple two point travel for initial development
int positionGeneration(int tick){
  if (tickState >= 0) return -0;                          // sample positions
  if (tickState < 0) return 0;                            //
} // end of positionGeneration

/////////////////////////// returns the next randomized location within the sinusoidal restrictions
int posRandGen(int tick){
  float secTime = millis()/1000.0;

  if (periodStart + wavePeriod < secTime){
    // previous cycle complete. need to random generate the next wave period
    periodStart = secTime;                                // remember the start time of new period
    float randValue = random(0,101);
    if (randValue < peakOccurPercent){                    // peak case desired
      wavePeriod = 1.0/peakFreq;                          // remember the period length of one cycle
      waveAmplitude = peakAmplitude;                      // remember the amplitude
    } else if (randValue < midOccurPercent + peakOccurPercent){                 // mid range case
                                                  desired
      waveAmplitude = random(smallAmplitude, peakAmplitude);
                                               // creates a value of amplitude that is between small and peak

      wavePeriod = 1.0/(sqrt(1.0*accelConst/waveAmplitude)/(2.0*pi));
    } else if (randValue < noAmplitudePercent + midOccurPercent + peakOccurPercent){
      waveAmplitude = random(smallAmplitude/2,smallAmplitude);
      wavePeriod = random(300,800)/1000.0;
    } else {                                              // small range case desired
      waveAmplitude = smallAmplitude;
      wavePeriod = 1.0/smallFreq;
```

```
    }
    return waveAmplitude*sin(2*pi/wavePeriod*secTime);  // return the first pos of new wave

  } else {
    // still performing a wave
    return waveAmplitude*sin(2*pi/wavePeriod*secTime);
  }

  return 0;
}

//////////////////////////// returns the position measured with linear potentiometer
int getPos(){
  int pos;                                   // -/+ inches x1000 length from origin
  float potInputValue;                          // 0~1023 value from potInput
  const float potConv = 512.0;                     // 512 pinInput/in
  const int potZero = 470;                        // centerpoint of potentiometer. Can range from 0 to
1023, but should be near the halfway point (512)
  potInputValue = analogRead(potPin);                 // read pot input voltage
  pos = (potInputValue - potZero)/potConv*1000;         // position in 1000ths of an inch

  return pos;
} // end of getPos()

///////////////////////////// sets the value of the pwmPin and direction
boolean setMotorVelocity(int velocity){               // velocity is -255~255
  int sign = 0;                              // determines sign of velocity and sets direction. Default if zero
  if(velocity >= 0) sign = 1;
  else if(velocity < 0) sign = -1;

  if(sign*velocity <= brakeRange){                 // checks if velocity is low enough to require braking
    digitalWrite(directionAPin, HIGH);
    digitalWrite(directionBPin, HIGH);                 // brake to GND
    //analogWrite(pwmPin, 0);
    return false;
  }

  if(sign == 1*motorSpinFlip){
    digitalWrite(directionAPin, HIGH);
    digitalWrite(directionBPin, LOW);
  }
  else if(sign == -1*motorSpinFlip){
    digitalWrite(directionAPin, LOW);
    digitalWrite(directionBPin, HIGH);
  }

  if (sign*velocity >= maxPwm && maxPwmToggle == 1){
      digitalWrite(ledPin, HIGH);                   // turn the ledPin on
      maxPwmToggle = -1;
    } else if (sign*velocity >= maxPwm && maxPwmToggle == -1){
```

```
      digitalWrite(ledPin, LOW);                         // turn the ledPin on
      maxPwmToggle = 1;
    }

  if(sign*velocity > maxPwm){
    analogWrite(pwmPin, maxPwm);
    return true;
  } else {
    analogWrite(pwmPin, sign*velocity + overcomeSticktion);
    return true;
  }
  return false;                                      // if it returns this line, something went wrong
} // end of setMotorVelocity()

boolean posSafeLimitOk(int posValue){
  if (abs(posValue) >= rangeLimit){
    return false;                                    // position is outside the safe limit!!
  } else {
    return true;                                     // position is within the safe limit.
  }
}
```

Appendix J – Pictures from Project Expo

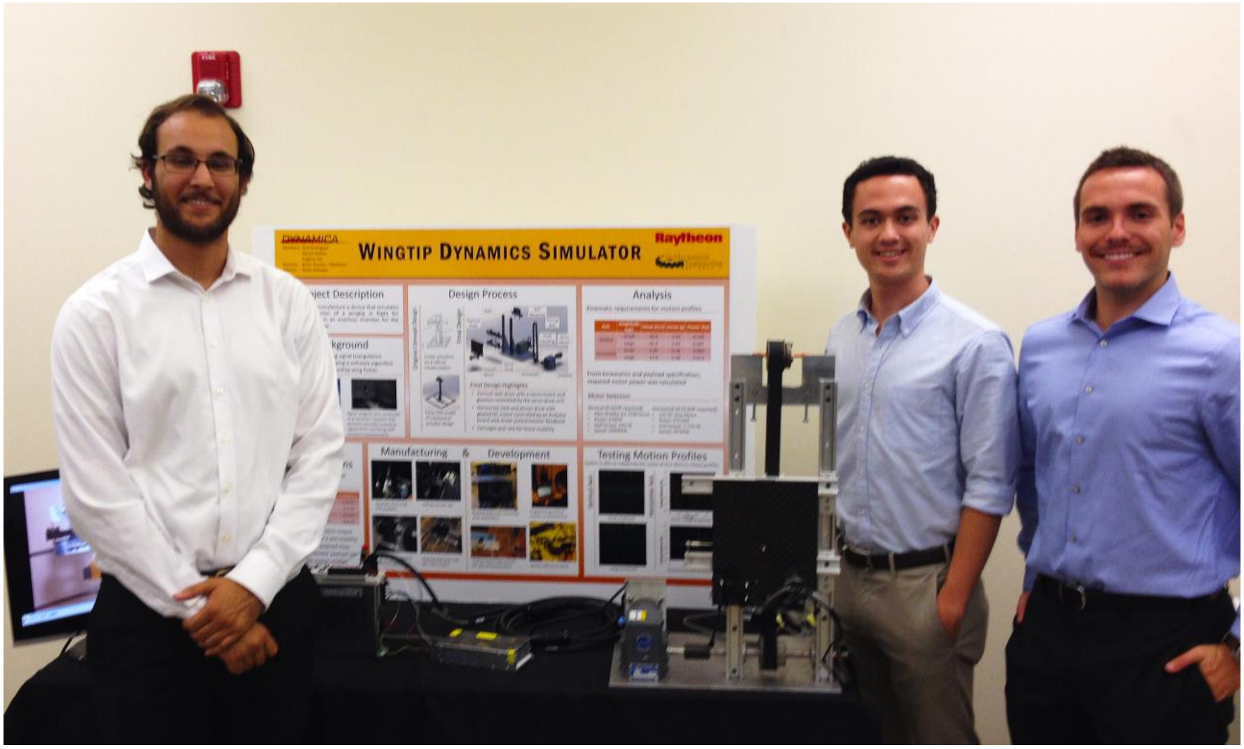


Figure 32. Team Dynamica members during the Senior Project Expo.
From left to right: Steven Rieber, Eugene Fox, and Nick Rodriguez.

Figure 33. Screenshot of the poster displayed at the project expo.

Appendix K – User Manual

Starts on next page.