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Design of a Thrust Stand for Electric Propulsion

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WESTERN MICHIGAN UNIVERSITY

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1 Abstract

Thrust stands are the industry standard device for measuring the low levels of thrust generated by electric propulsion devices. Western Michigan University's Aerospace Laboratory for Plasma Experiments is home to several electric propulsion devices and is in the process of obtaining a pulsed plasma thruster in partnership with the Western Aerospace Launch Initiative. The lab currently has no way of measuring the true thrust force generated by these devices. A thrust stand has been designed specific to the micro-Newton thrust range and the constraints inherent to the facilities in which it will operate.

Table of Contents

Table of Figures

Table of Tables

2 Introduction

2.1 Background: Space Propulsion

Spacecraft propulsion systems can be broken into two major categories: chemical propulsion and electric propulsion. Each of these systems are commonly used and have a variety of applications. Before either system is flown, it undergoes rigorous testing and experimentation to minimize the risk of failure. Perhaps the most fundamental performance parameter that must be characterized is the true thrust force produced by the system.

Chemical propulsion devices, such as rocket engines, utilize combustion and accelerate the combustive by-products through a nozzle. These systems can provide high thrust (in the magnitude of 10^6 Newtons) but do so with low efficiency. The liquid and/or solid propellant along with the required oxidizers are carried onboard the rocket. This adds substantial weight in addition to the weight of the payload and bus, increasing the thrust required to successfully complete operational objectives. Chemical propulsion is not a viable option for long spaceflight missions, however it is currently the only known way to launch payloads from the surface of the earth into orbit.

Electric propulsion (EP) devices can be grouped into three primary categories based on the way in which propellant is accelerated, however, the fundamental operating principles are the same for each device: electric propulsion utilizes electricity to generate thrust. This can be done by way of electrothermal, electrostatic, and electromagnetic thrusters. Some commonly used EP thrusters are Hall thrusters (electrostatic), ion engines (electrostatic), resistojets (electrothermal), and pulsed plasma thrusters (PPTs) (electromagnetic). Hall thrusters and ion engines ionize a gas propellant and use electric and magnetic fields to accelerate exhaust particles. Resistojets heat the propellant and accelerate it through a nozzle. PPTs use a pulsed discharge to ionize a solid propellant (usually Teflon) and accelerate exhaust particles with electromagnetic effects. In general, EP is highly efficient but produces low thrust. Depending on the needs of the mission, some EP devices can produce a large thrust force given long burn times, but these devices are most commonly used for station keeping and orbital maneuvers, which require small magnitudes of thrust (ranging from 10^1 – 10^{-6} Newtons). Because of the low weight of onboard propellant and their high efficiencies, EP is the leading technology for current and future in-space mobility.

2.2 Thrust Measurement

The thrust-to-weight ratio is a measure of the weight of a thruster to the force of thrust it produces and is a common way to evaluate thruster performance. This ratio for EP devices is significantly higher than the thrust-to-weight ratio of a chemical system. The testing and experimentation implications of the thrust-to-weight ratio for chemical devices translates into requiring large facilities and the use of load cells to measure the true thrust produced by the system. Load cells are not adequate devices for measuring the substantially lower thrust of much lighter EP systems. The conventional method for measuring the true thrust of EP systems is by using a thrust stand.

The principles of load cells and thrust stands are fundamentally the same, but the design, fabrication, and use are entirely different. Both probes measure a displacement. Load cells measure the strain within a metal to calculate thrust. Thrust stands are essentially a spring-mass-damper system that measures a physical displacement of a pendulum arm. There are three configurations of pendulum thrust stands: inverted, hanging, and torsional. [1].

2.2.1 Hanging Pendulum

Hanging pendulum configurations require the thruster to be secured on the end of a moment arm hanging vertically below the pivot point. This configuration is the least complex and easiest to manufacture [5]. The gravity force acts as a stabilizer, making them inherently stable systems.

Hanging pendulums typically have a larger moment arm to increase sensitivity. The natural stiffness of the stand is negligible compared to the gravitational contributions; thus, the sensitivity is primarily a function of the arm. This can be restricting for smaller vacuum chambers.

Because reasonable sensitivity for this configuration requires a larger moment arm, hanging pendulums have a high heat resilience. The electrical components are housed on the top plate giving distance between sensitive components and the heat-generating thruster, minimizing thermal conduction and thermal management needs.

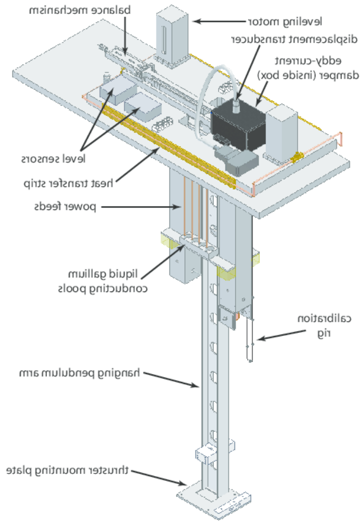

Figure 1: VAHPER Hanging Pendulum Thrust Stand [2]

Figure 1 depicts the Variable Amplifications Hanging Pendulum with Extended Range (VAHPER) thrust stand which was designed to extend the use of hanging pendulums limited thruster ranges by adding variable sensitivity through the use of balance mechanisms [2]. Using modern technology and new innovations, hanging pendulums have been adapted to wider ranges of sensitivity and accuracy for a wider range of thrusters [3].

2.2.2 Inverted Pendulum

Inverted pendulum configurations utilize a pendulum in which the center of mass is above the pivot point, therefore the thruster is attached to the top plate of an inverted pendulum. In this configuration, the gravitational force is a destabilizing force, making inverted pendulum thrust stands inherently unstable.

The stiffness of the thrust stand is negligible compared to the gravitational vector. Thus, inverted pendulums have a higher sensitivity for a smaller moment arm making them compact and well-suited for smaller chambers. While the instability is good for sensitivity, it also means that the thrust range capable of being measured by an inverted pendulum is extremely limited. Also, the compact nature of this configuration means it has a low heat resilience. Inverted pendulums usually utilize a thermal shrouding for thrusters to minimize thermal effects. Figure 2 depicts an inverted pendulum design from Bagozici Space Technologies Laboratory utilizing counterweight to minimize gravitational effects and to lower facility noise and vibration effects [4].

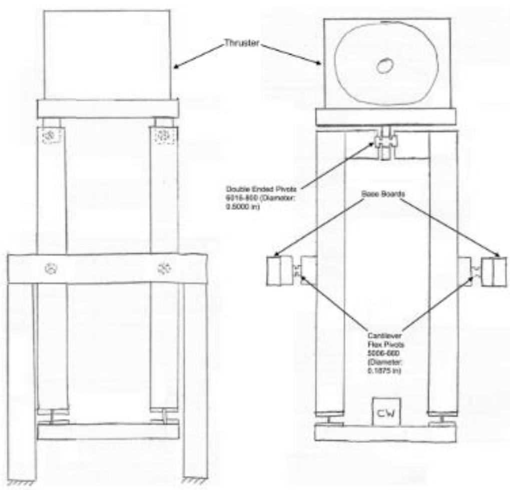

Figure 2: BUSTlab Inverted Pendulum Thrust Stand Design[4]

2.2.3 Torsional Pendulum

Torsional pendulum configurations are similar to hanging pendulum configurations in that they operate with the thruster attached to the end of a moment arm. However, unlike the other configurations, the moment arm is horizontal. This eliminates the effect of the gravitational force on the system, meaning that the weight of the thruster has no effect on thrust measurements.

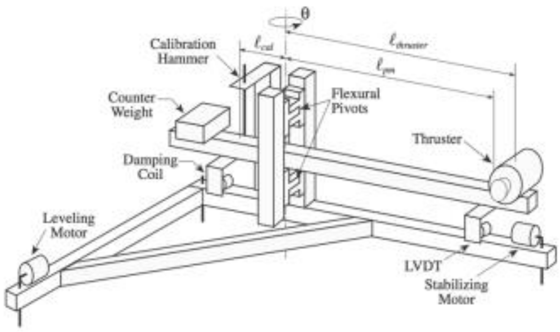

Figure 3: Torsional Thrust Stand Design [5]

Torsional configurations are useful for a wide range of thrust-to-weight ratios. The spring constant of torsional stands is only a function of the material used for the thruster in the joint and the moment arm, so the sensitivity of the system can be very high. However, the sensitivity, like in hanging pendulums, is a function of mainly the moment arm length. Therefore, to achieve high sensitivity, the arm must be long and therefore torsional pendulums have a tendency to be larger and non-conducive to smaller vacuum chambers. Figure 3 shows a schematic for a general torsional thrust stand [5].

3 Project Overview

3.1 Problem/Need Statement: Thrust Measurement for ALPE and WALI

The Aerospace Laboratory for Plasma Experiments (ALPE) is a lab at Western Michigan University's (WMU) College of Engineering and Applied Sciences (CEAS) founded and operated by Dr. Kristina Lemmer that performs a variety of EP experimentation. The Western Aerospace Launch Initiative (WALI) is a student organization also at WMU's CEAS campus dedicated to the design, fabrication, testing, and launch of a CubeSat. WALI is currently working on the Optical Plasma Spectroscopy CubeSat (OPS-Cube) mission, which is a stepping stone in the development of on-orbit EP thruster emission spectroscopy. This technology will allow for on-orbit EP system diagnostics and propellant identification. WALI and ALPE work in partnership to achieve the shared goals of understanding in-space EP thruster behavior.

The ALPE/WALI partnership is the process of obtaining a PPT that will be used for the OPS-Cube mission. This thruster will be used as both a plasma source for on-orbit optical emission spectroscopy (OES) and to provide the means to perform a novel orbital maneuver. In order to ensure a successful change in orbital trajectory and to accurately evaluate in-space thruster performance, the true thrust must be measured in ground facilities before flight.

ALPE is also host to a Hall thruster, ion engine, and several cathodes, but does not have a method to measure the true thrust generated by any of them. The lab currently uses probes that aid in thrust estimations, but continued research and EP education requires a full characterization of WMU's EP devices. Thrust stands for EP devices are currently not available as commercial-off-the-shelf (COTS) products, and even if they were, the requirements of design and fabrication would make them very expensive. They must be specifically designed for a customer's needs. This design and fabrication process requires too much time and funding for the average WALI or ALPE volunteer student researcher to complete.

3.2 Objective of Work

The objective of this project was to design a thrust stand to be used in the ALPE vacuum chamber that WALI will also utilize for pre-flight PPT testing. The thrust range of the PPT has been prioritized since thruster performance must be studied prior to flight. The additional thrusters operated in ALPE are used for research purposes only, however, there is the potential that they can be tested using the stand.

The following objectives were defined to drive the success criterion and therefore the system requirements:

OBJ-1: Design a thrust stand capable of measuring the true thrust produced by a pulsed plasma thruster for use in the Aerospace Laboratory for Plasma Experiments

OBJ-2: Design a thrust stand for use as an educational tool in electric propulsion academic research

Consideration has been given to create a device that is easy to handle and operate. Each element of its use (setup, calibration, and operation) will be thoroughly documented once fabrication is complete.

3.3 Scope of Work: Success Criterion

The following success criterion was defined to drive the design requirements:

SC-1: The thrust stand shall measure pendulum arm displacement induced by an EP thruster and convert the displacement to units of force.

4 Design Requirements

To keep fabrication costs to a minimum and prevent overdesign, system requirements must be defined before design can begin. The following sections identify this design's requirements. The full requirement verification matrix along with definitions, descriptions, and acronyms can be found in Appendix A.

4.1 Facility Interface – Mechanical

ID	Maturity	Source ID	Requirement Statement	Verification Method	Comments
FI-01	High	OBJ-01	The thrust stand shall be able to be contained within the ALPE 1.5-m long, 1-m diameter vacuum chamber	Inspection	
FI-02	High	FI-01	The thrust stand footprint length shall not exceed 30 in.	Inspection	Length of the internal 80-20 structure is 31 in.
FI-03	High	FI-01	The thrust stand footprint height shall not exceed 20 in.	Inspection	Height of the internal 80-20 structure is 24.5 in.
FI-04	High	FI-01	The thrust stand footprint width shall not exceed 40 in	Inspection	Width of the internal 80-20 structure in the front half of the chamber is 40 in.
FI-05	High	OBJ-01	The thrust stand shall connect to the Aluminum 80-20 structural framing system installed in the ALPE vacuum chamber	Demonstration	

Table 1: Facility Interface Mechanical Requirements

The thrust stand must be operated inside the vacuum chamber in ALPE, which is a 1.5-m long, 1-m diameter cylinder. The stand must be capable of easily fitting inside when the chamber is closed. The stand is designed to attach to the aluminium 80/20 structural framing system that already exists inside the chamber. Figure 4 shows a model of the pre-existing 80/20 structure with the driving dimensions.

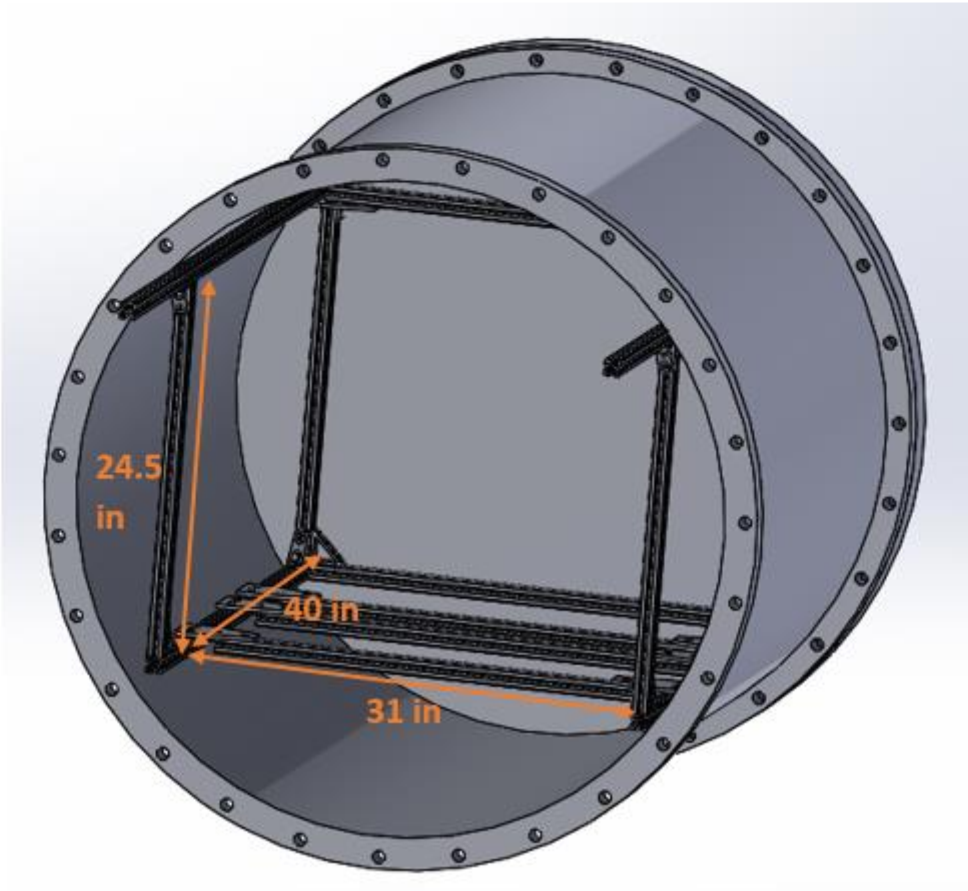

Figure 4: ALPE Chamber 80/20 Structure

4.2 Facility Interface – Power, Signal, and Gas

ID	Maturity	Source ID	Requirement Statement	Verification Method	Comments
FI-06	High	OBJ-01	The thrust stand shall be capable of interfacing with the existing facility power, signal, and gas connections	Demonstration	
FI-07	High	FI-06	Four type K thermocouples shall connect to the thrust stand from the facility	Demonstration	A quad type-K thermocouple feedthrough is available for chamber

Table 2: Facility Interface Power, Signal and Gas Requirements

The thrust stand requires connections for supply power, data acquisition (DAQ), and gas for thruster propellant. The ALPE facilities have a variety of chamber feedthroughs and connections for which the stand has been designed to utilize for convenience and cost effectiveness. Figure 5 shows the back-exterior wall of the chamber with a BNC feedthrough on the top left, a thermocouple feedthrough on the top right, a gas feedthrough on the bottom left, and a power feedthrough on the bottom right.

Figure 5: ALPE Chamber Feedthroughs

4.3 Handling and Storage

ID	Maturity	Source ID	Requirement Statement	Verification Method	Comments
HS-08	High	OBJ-01	The thrust stand shall be easily installed/removed from the ALPE vacuum facility.	Demonstration	Thrust stand must be easily installed and removed with little to no physical challenge by a single person
HS-09	High	HS-08	The thrust stand shall have a weight ≤ 50 lbs	Inspection	OSHA limit compliance

Table 3: Handling and Storage Requirements

For convenience and safety, the thrust stand has been designed for easy storage and handling. It meets OSHA lifting constraints and should be able to be handled by a single student without major physical disability.

The stand has been designed to be placed on a breadboard for setup and transportation. Breadboards are commonly used to increase efficiency and accuracy in labs for experimental setup. A set-up can first be created on a breadboard outside of the chamber and placed inside when it is ready for use. Handles have been added to the breadboard plate for additional safety and convenience.

4.4 Thruster Interface

ID	Maturity	Source ID	Requirement Statement	Verification Method	Comments
TI-10	High	OBJ-01 OBJ-02	There shall be a thruster interface designed for easy thruster attachment	Demonstration	

Table 4: Thruster Interface Requirements

During use, it is crucial to the safety of both students and the lab equipment that the thruster being tested can be easily and securely attached to the stand. A breadboard plate has been utilized for the stand-thruster interface for standard fastening and to accommodate variability in thruster size. The plate dimensions are such that any of the lab's EP thrusters will safely fit.

4.5 Fabrication

4.5.1 Requirement Verification Matrix

ID	Maturity	Source ID	Requirement Statement	Verification Method	Comments
FAB-11	High	OBJ-01	Thrust stand shall be simple to machine and assemble using WMU machine shop equipment	Demonstration	
FAB-12	High	OBJ-01	The thrust stand and all its components shall utilize low-outgassing materials	Inspection	Low-outgassing materials protect the facility and ensure efficient pump-down to high-vacuum
FAB-13	High	HS-09 FAB-12	The thrust stand structure shall be constructed with Aluminium 6061-T6.	Inspection	

Table 5: Fabrication Requirements

Many of the components and materials that will be used for fabrication will need to be machined and/or modified in some capacity. The design is such that all machining and assembly will be able to be done on WMU's CEAS campus using the equipment and tools available to students. Designing to this requirement reduces cost and assembly complexity, which also contributes to product quality assurance.

It is critical that every component and material used for fabrication has low out-gassing properties when exposed to high vacuum. Materials that have high out-gassing properties essential fall apart when exposed to low pressures. Beyond compromising the product, material out-gassing increases the time it takes to pump a chamber down to vacuum pressures, which prolongs experimentation and is avoided as much as possible. The particles that out-gas stick to the walls of the chamber and other facility components resulting in contamination and required cleaning.

4.6 Performance

ID	Maturity	Source ID	Requirement Statement	Verification Method	Comments
PFM-14	High	OBJ-01	The thrust stand shall convert a lateral force into an electrical voltage signal.	Testing	The voltage signal will be read by the lab DAQ.
PFM-15	Medium	PFM-14	The thrust stand shall have a sensitivity of 10mV/μN ± 1mV/μN.	Testing	
PFM-16	Medium	PFM-14	The thrust stand shall have a resolution of 1 μN.	Testing	
PFM-17	Medium	PFM-14	The thrust stand shall have an accuracy of 10 μN.	Testing	
PFM-18	Medium	PFM-14	The thrust stand shall have a response time capable of measuring a single impulse from the BMP220.	Testing	
PFM-19	High	OBJ-01	The thrust stand shall be capable of being precisely levelled to ensure measurement accuracy	Demonstration	

Table 6: Performance Requirements

Through extensive literature studies, performance metrics have been determined for the range of thrust in which this stand will be measuring. These metrics can be found in Table 6 above.

When the thrust stand is in operation, it is very important that the system is perfectly level. The measurements are ideally measured when the thrust vector is completely horizontal. Once the thrust stand is attached to the 80/20 framing system, it is likely some adjustments will need to be made.

4.7 Thermal Management

ID	Maturity	Source ID	Requirement Statement	Verification Method	Comments
TM-20	Medium	OBJ-01	The thrust stand shall be thermally managed to prevent sensitive components from overheating	Test	

Table 7: Thermal Requirements

Depending on the thruster, thermal management could potentially be an issue. PPT's do not generate enough heat to compromise the sensitive components, however Hall thrusters do. The thrust stand should be able to manage the heat produced by the thruster so that the instrumentation is not affected.

5 Constraint Identification and Analysis

5.1 Technical

The technical constraints imposed on this design primarily stem from the facilities in which the stand will be used. In order for the design to have utility for student researchers in ALPE, it must be compatible with the lab vacuum chamber, thrusters, equipment, and mitigate general lab noise.

Thrust stands are sensitive probes prone to moment arm displacement from ambient vibrations. These constraints have all been accounted for and are reflected in the requirements developed for the design.

5.2 Economical

The funding for this project came from the design team's Undergraduate Research Excellence Award, which totals $2,000.00. This budget also serves to make this design accessible to other student researchers seeking to make an affordable thrust stand at other universities.

5.3 Design Schedule

The timeline allowed for this design to reach completion was approximately eight months. This included the time required for project selection, faculty advisor selection, and several major holidays in which the team took time off from the project. Both team members managed full time undergraduate classes and participation in the WALI student organization throughout the duration of the design as well.

6 Mathematical Model

6.1 System Dynamics

Pendulum thrust stand configurations can be modelled as spring-mass-damper systems. Equation (1) shows the fundamental equation of motion for the thrust stand with a force F(t) of thrust from the thruster. Equation (2) shows the time evolution of the thruster for different damping ratios. The derivation of this solution can be found in Appendix B.

$$I\ddot{\theta}(t) + c\dot{\theta}(t) + k\theta(t) = F(t)L \tag{1}$$

$$\theta(t) = \begin{cases} \frac{I_{bit}L_T}{I{\omega_n}^2}\left(\frac{1}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\sin(\omega_n\sqrt{1-\zeta^2}t)\right) & \zeta < 1\ (underdamped) \\ \frac{I_{bit}L_T}{I{\omega_n}^2}\omega_n t e^{-\omega_n t} & \zeta = 1\ (critically\ damped) \\ \frac{I_{bit}L_T}{I{\omega_n}^2}\left(\frac{1}{2*\sqrt{1-\zeta^2}}\left[e^{-(\zeta-\sqrt{\zeta^2-1}\omega_n t} - e^{-(\zeta+\sqrt{\zeta^2-1}\omega_n t}\right]\right) & \zeta > 1\ (overdamped) \end{cases} \tag{2}$$

As suggested in Recommended Practice for Thrust Measurement's in Electric Propulsion Testing [5], a damping ratio of $0.4 < \zeta < 0.8$ can be used to gain a good response time to a step input. Figure 6 shows a normalized angular position oscillation as a function of time measures in natural periods in response to an impulse.

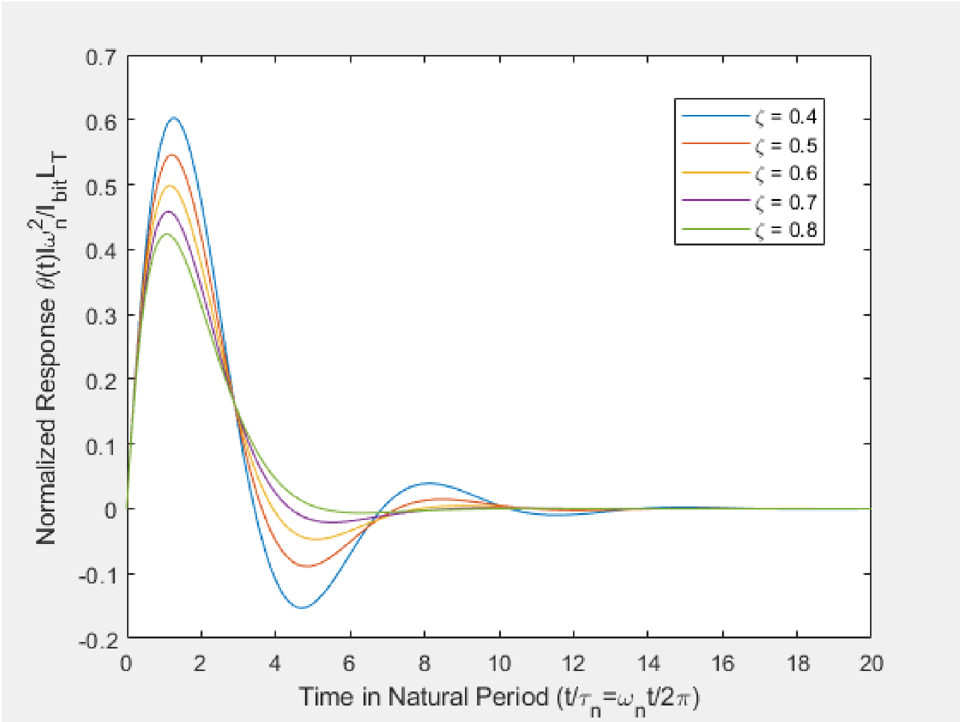

Figure 6: Angular Position as a function of time

To find the angular deflection, the natural frequency and the moment of inertia of the thrust stand moment arm must be known. These numbers can be estimated as the deign progresses, but it is far more common to find the normalization factor experimentally with a calibration test run before the experiment.

6.2 Configuration Selection: Decision Matrix

A decision matrix was designed to quantify the pros and cons of each standard pendulum configuration to determine the optimal design for this system. The design criteria were created with the specifications unique to this project and timeline for completion in mind. Table 8 is the matrix. The design criteria are listed in order of the weighted factor, and therefore by importance to the project. An overall score of 100 was chosen to create a wide range of evaluation potential. For each criterion, a score of 100 is the best possible outcome, and a score of 0 is the worst. The "Overall Score" is calculated by summing all design criteria for a particular configuration and multiplying by the respective weight factor.

	Design Criteria	*Manufacturing Difficulty*	*Thrust Range*	*Availability of Literature*	*Size Constraints*	*Typical Sensitivity Ranges*	***Overall Score***
Configuration	***Weight Factor***	10	10	20	30	30	**100**
Inverted Pendulum		30	10	80	90	30	**56**
Torsional Pendulum		75	90	75	50	90	**73.5**
Hanging Pendulum		90	30	30	20	30	**33**

Table 8: Design Decision Matrix

6.2.1 Decision Matrix Design Criteria

The design criteria were selected to reflect fundamental requirements that vary between configurations. The timeline of the project as well as the facility constraints upon this project were a major factor for the criteria. The literature and manufacturing difficulty are based on time constraints. A larger literature pool for a design makes for a faster and easier design process, and the easier it is to manufacture, the faster the manufacturing process will go. The size constraint criteria represent the size constraint of the vacuum chamber. The typical sensitivity range and thrust stand range represent the stands ability to be used by multiple thrusters. While the scope of this project is defined by the need to measure the thrust of the PPT, ALPE is a host to many thrusters with varying thrust ranges. The thrust stand should be able to accommodate several of the thrusters.

From the decision matrix, the torsional pendulum design was chosen. The biggest downfall of the design being the size constraints. From preliminary calculations, it is believed that a sufficient size can be designed to fit the ALPE chamber. The torsional design gives the greatest opportunity for large thrust range and sensitivity range, and therefore has the greatest potential to be used with a variety of thrusters.

6.3 Dimensional Modelling

After a torsional thrust stand was selected, dimensional modelling as preformed to get rough estimates for the dimensions to start creating the CAD model. The stand is being designed to the BMP-220 Busek PPT with a mass of 0.5 kg and a rough footprint of 95 mm by 95 mm. The thruster moment arm was set at 15 in for ease of manufacturing. In order to determine the best mass and position for the counterweight, the mass of the counterweight was varied from 0.1 to 5 kg in 0.1 increments. The length of the counterweight moment arm was calculated to follow static equilibrium, as shown in equation (3).

$$\frac{m_T}{l_T} = \frac{m_{cw}}{l_{cw}} \tag{3}$$

To determine the optimal position and weight for the counterweight, the mass moment of Inertia in the moving axis, also called the yaw moment of inertia, and one stationary axis, the roll moment of inertia, were considered. Figure 7 depicts the mass moments of inertia on the moment arm. The yaw moment of inertia is determined by considering the counterweight and the thruster as point masses and finding the mass moment of inertia of the system about the yaw direction. This simply comes to be the parallel axis theorem of the two point masses, as seen in equation (4). For the roll moment of inertia, as seen in equation (5), the thruster cannot be considered a point mass and therefore the footprint area is used to calculate an estimated roll moment of inertia for the thruster cantered around the roll axis. The vertical, or z directional, distance of the counterweight is also varied to optimize the placement of the counterweight in the vertical direction. With this the quotient of the yaw and roll moment of inertia was taken. The optimum value for this quotient will be the smallest value. The smallest value corresponds to a high roll moment, or a high reactance to roll, and a low yaw moment, or a low resistance to yaw. It was found, using the code in Appendix C, that a larger mass at a smaller moment arm was optimal for the counterweight. For manufacturing reasons, the minimum value was not used, as it would place the counterweight too close to the central axis and be difficult to fit a counterweight within the space given. Instead, similarly to the thrust stand produced at Arizona State a 10:1 ratio was used [6]. The thruster was placed at 15 in from the central axis and a 5 kg counterweight is placed at 1.5 in from the central axis.

$$I_{yaw} = m_T l_T^2 + m_{cw} l_{cw}^2 \tag{4}$$

$$I_{roll} = \frac{1}{2} m_T (a^2 + b^2) + m_{cw} l_{cw}^2 \tag{5}$$

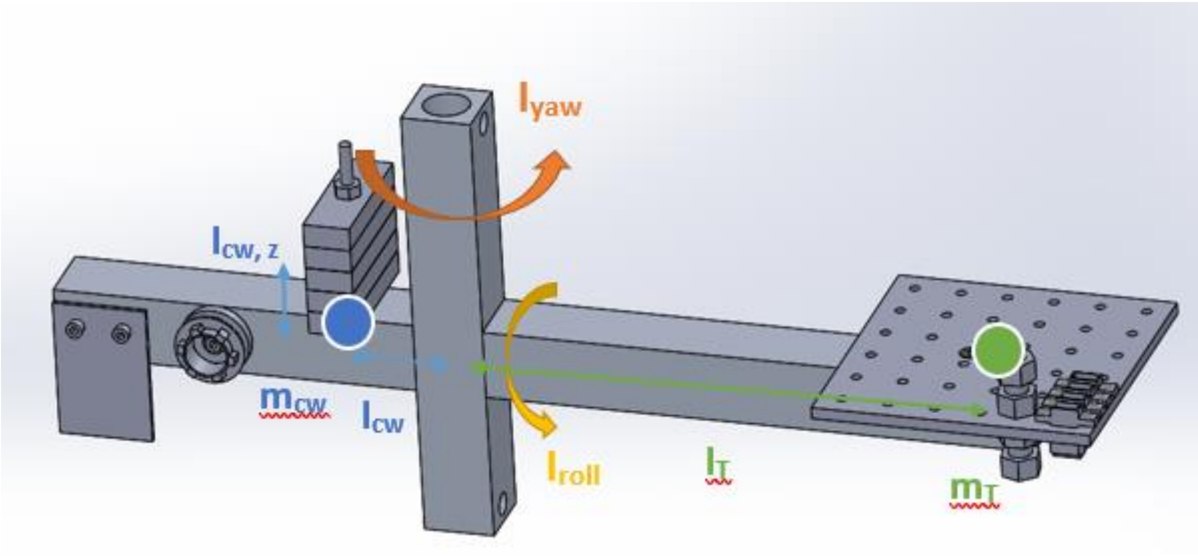

Figure 7: Mass Moment of Inertia Diagram

7 Final CAD Model

Following the requirements and initial dimesional modelling, a thrusts stand was designed. Figure 8 shows the full design. The following sections cover the component selection and requirements fulfilled by the design.

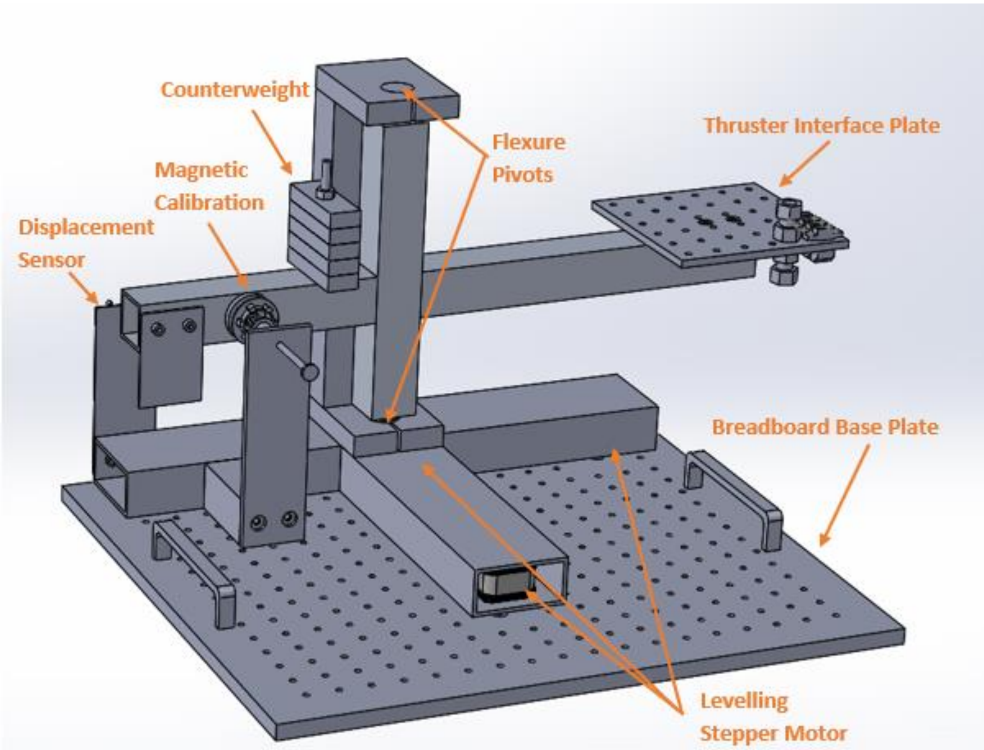

Figure 8: Full Thrust Stand Design

7.1 Structural Model

The thrust stand designed is a torsional thrust stand comprised of a stationary base and a moment arm free to move about one axis. The stationary base is formed with a breadboard base with handles and a structural support for the moment arm. Figure 9 shows the major assemblies with the moment arm in grey, the structural support in purple, and the breadboard base in teal.

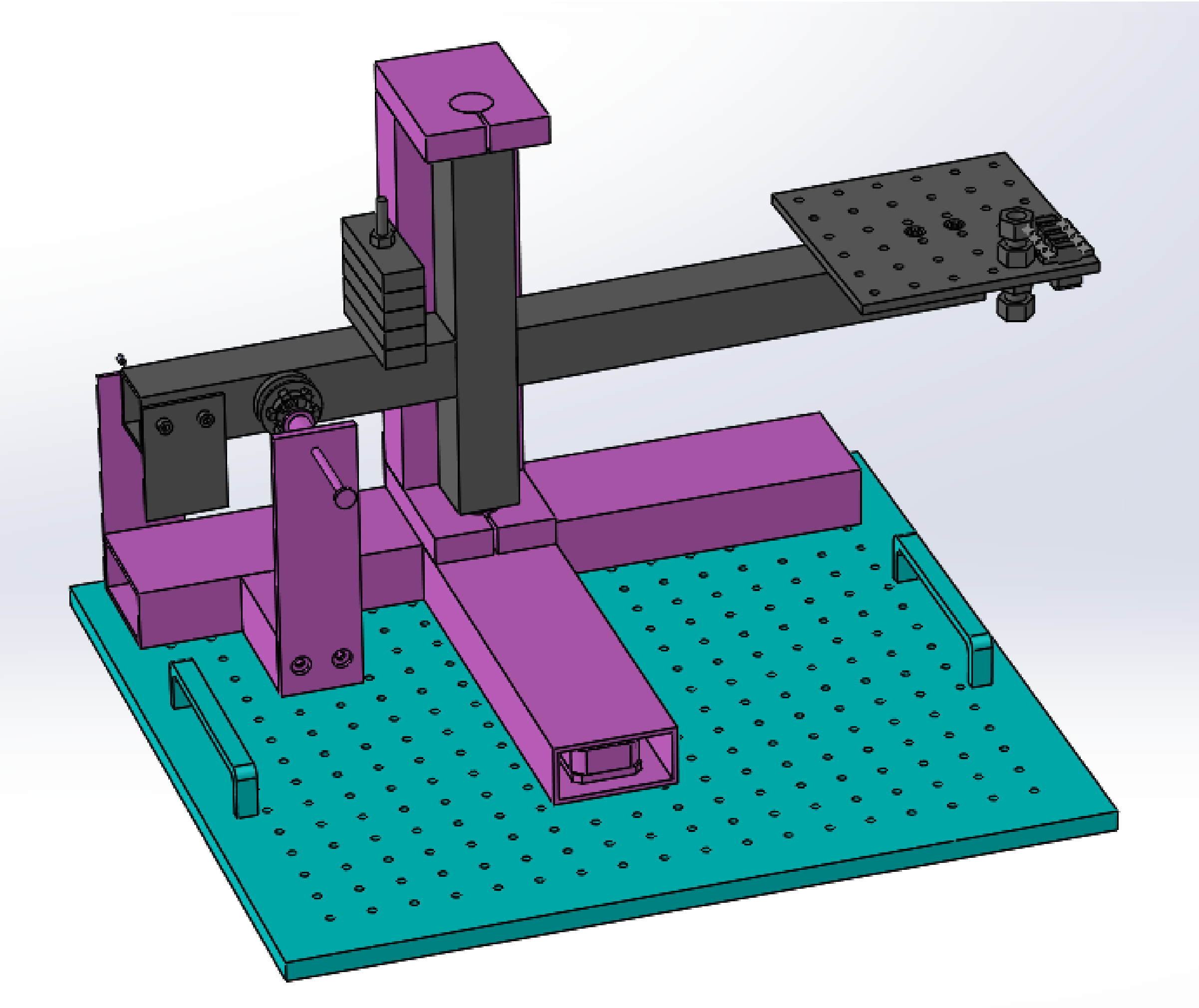

Figure 9: Thrust Stand Major Assemblies

The breadboard base, teal in Figure 9, serves as a base for the entire structure as well as a levelling point for the stepper motors. The base has handles, shown in Figure 10, on either side of the base offer easy transportation of the thrust stand, satisfying requirement HS-08. The breadboarding of the base gives multiple anchor points to the 80/20 structure inside the chamber, satisfying requirement FI-05.

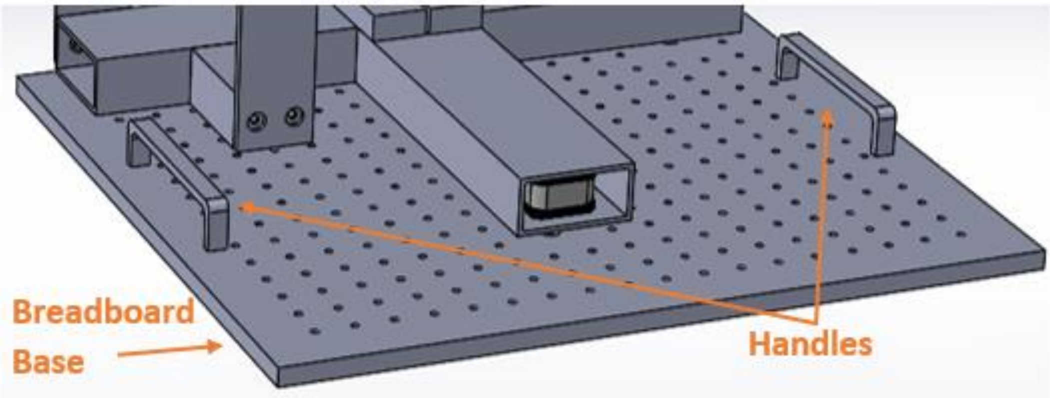

Figure 10: Breadboard Base Handles

The structural support, purple in Figure 9, offers support for the moment arm about its free axis as well as houses the instrumentation for calibration and displacement measurement. The structural support also houses the stepper motors for levelling, satisfying requirement PFM-19. Three stepper motors have been included in the design at strategic points that allow for the system to be precisely levelled before the chamber is sealed.

The moment arm, grey in Figure 9, is the moving component of the thrust stand. With the thruster on one end and the counterweights on the opposing end, the moment arm rotates around a central axis containing flexure pivots that allow the rotation with minimum friction.

All mounting holes and fasteners are sized for M5 fasteners. This is to simplify the fabrication and assembly process. By using only M5 fasteners, requirement FAB-11 is met with a simple to machine design.

7.2 Components and Material Selection

The primary material selected for fabrication is the aluminium 6061-T6 alloy. Its major alloying elements are magnesium and silicon. It is one of the most commonly used alloys of aluminium and is widely available and relatively inexpensive. It has great mechanical properties, is highly resistant to corrosion, easy to machine, and is frequently used for vacuum pressure applications. Aluminium 6061-T6 is also relatively lightweight, which contributes to the ease and safety of handling of the product.

The total component List can be seen in

Appendix D: Component List. The following sections describe the component selection of each subassembly.

7.2.1 Structural Components

Table 9 shows the components needed for the structure of the thrust stand. Aluminium was chosen as the key material for the structural components because of its machinability, low outgassing, and Helping satisfy requirements FAB-12, FAB-13, and HS-09.

Component	Vendor	Cost per unit	Number Needed	Total cost	Component details
Structure					
Aluminium Rectangular tube 10 in	BuyMetal	12.06	1	12.06	1.5" x 3" x 10 " with 0.125" thickness
Aluminium Rectangular tube 18 in	BuyMetal	18.02	1	18.02	1.5" x 3" x 18 " with 0.125" thickness
Aluminium Rectangular tube 12 in	BuyMetal	10.81	1	10.81	1.5" x 3" x 12 " with 0.125" thickness
Aluminium Square Tube 16 in	BuyMetal	14.95	1	14.95	1.5" x 1.5" x 16" with 0.125" thickness
Aluminium Square Tube 3 in	BuyMetal	8.1	1	8.1	1.5" x 1.5" x 3" with 0.125" thickness
Aluminium Square 9.5 in	BuyMetal	16.55	1	16.55	1.5" x 1.5" x 9.5"
Aluminium Plate 0.313" thick	BuyMetal	35.65	1	35.65	5" x 5" x 0.313"
Aluminium Plate 0.75" thick	BuyMetal	83.7	2	167.4	4 x 3 x 0.75"
Aluminium Plate 0.5" thick	BuyMetal	221.13	1	221.13	18 x 20 x 0.5"
M5 x 10 mm screw	Home Depot	0.34	12	4.08	6 for base, 4 for arm, 10 for flexure pivot connection
M5 Nut	Home Depot	0.265	10	2.65	6 for base, 4 for arm
M5 x 50 mm	Home Depot	0.69	2	1.38	2 for base flexure pivot connection
Stepper Motor	Lin Engineering	40.8	3	122.4	4118S-04P
Inclinometer	Analog Devices Inc.	112	2	224	Part Number: ADIS16209/PCBZ
Flexure Pivot	Riverhawks Flex Pivot	192	2	384	1" diameter

Table 9: Structural Components

The components for the structure were chosen from COTS components. Rectangular Tubes and squares were utilized for the structural support, and moment arm. The Design has an overall footprint of 18 in by 20 in by 14.06 in, thus satisfying the footprint requirements in FI-01, FI-02, FI-03, and FI-04, as seen in Figure 11.

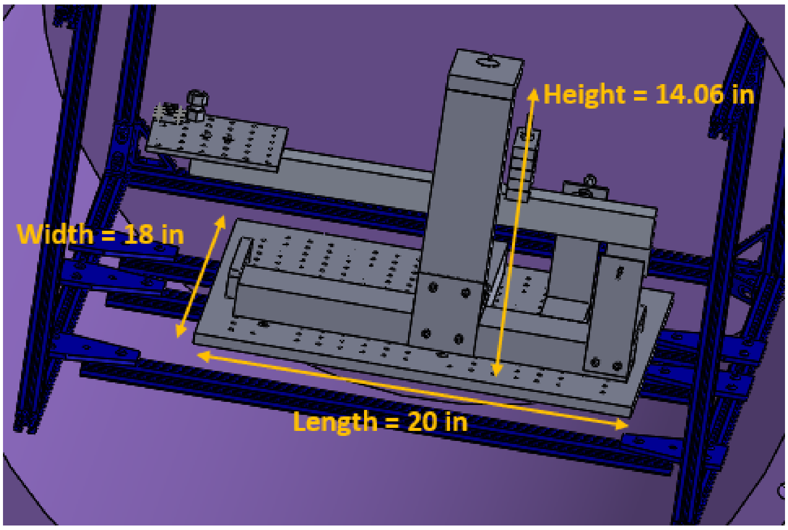

Figure 11: Thrust Stand Footprint

7.2.2 Counterweight Components

Carbon steel was chosen for the counterweights because of its high density, giving a larger mass in a smaller volume compared to other materials. The carbon steel will be machined into 1 kg and 0.5 kg counterweights to be used in unison to reach a desired counterweight mass. The counterweights are machined with a hole through their middle to be attached at the counterweight attachment screw, seen in Figure 12.

Component	Vendor	Cost per unit	Number Needed	Total cost	Component details
		Counterweight			
Carbon Steel	BuyMetal	7.2	5	36	1" x 1" x 3"

Table 10: Counterweight Components

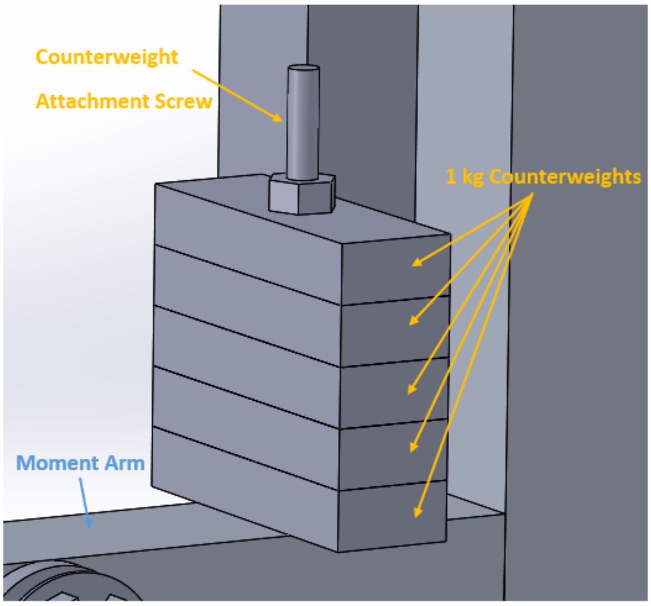

Figure 12: Counterweight System

7.2.3 Instrumentation Components

In order to convert a thrust into a readable voltage, thus satisfying the requirement PFM-14, an Linear Variable Displacement Transformer (LVDT) is used to read a displacement. The voltage from the LVDT is converted into a force following a calibration curve, discussed further in the following section. For this design, a non-contact LVDT (NC LVDT) was chosen to minimize the losses in the system. The NC LVDT measures a displacement of target, seen in Figure 13. A NC LVDT from LORD Sensing Microstrain was chosen for this project. While the sensitivity, accuracy, resolution, and response time of the system are factors that can only be determined by running experiments with the whole system, they are extremely dependent of the corresponding value of the LVDT used. The LORD Sensing Microstrain NC LVDT has a micron sensitivity, a resolution of 0.1% full scale, an accuracy at 25 degrees Celsius of 0.2 to 0.1 %, and a response of 800 Hz. These values are within the values set for the system in requirements PMF-15, PMF-16, PMF-17, and PMF- 18.

Component	Vendor	Cost per unit	Number Needed	Total cost	Component details
Instrumentation					
NC-LVDT	LORD Sensing Microstrain	425	1	425	LVDT

Table 11: Instrumentation Components

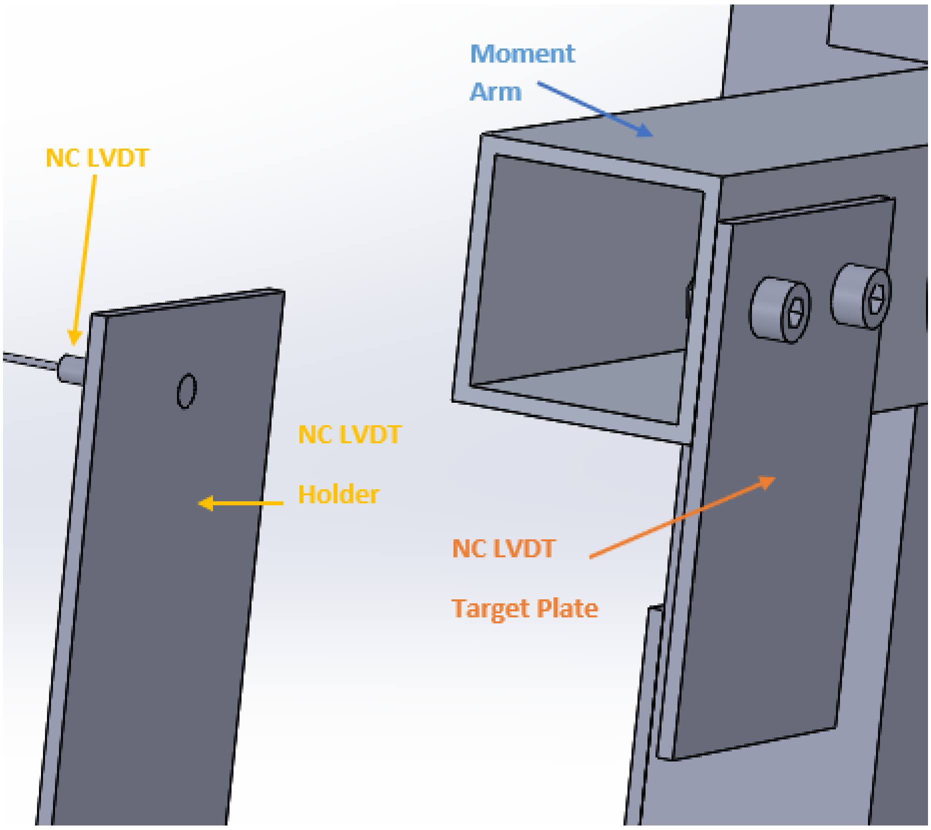

Figure 13: NC LVDT Set Up

7.2.4 Calibration Components

A magnetic calibration set up was modelled after the micro-Newton thrust stand at Space Plasma and Electric Propulsion Laboratory at Beihang University [7]. The system uses permanent magnets attached to the moment arm to create a magnetic field. An impulse is created by sending current through the wire coil for a known amount of time creating a second b-filed and therefore a pulsed force on the system. The system is calibrated by exerting several known impulses on the system and mapping the displacements with the impulses. Figure 14 shows the system in the cad model. Table 12 shows the components for the system.

Component	Vendor	Cost per unit	Number Needed	Total cost	Component details
Calibration System					
Permanent Magnet	AMFMagnets	0.68	12	8.16	
Aluminium Bar 0.5" thick	BuyMetal	4.85	1	4.85	0.5 " x 1"

Table 12: Calibration Components

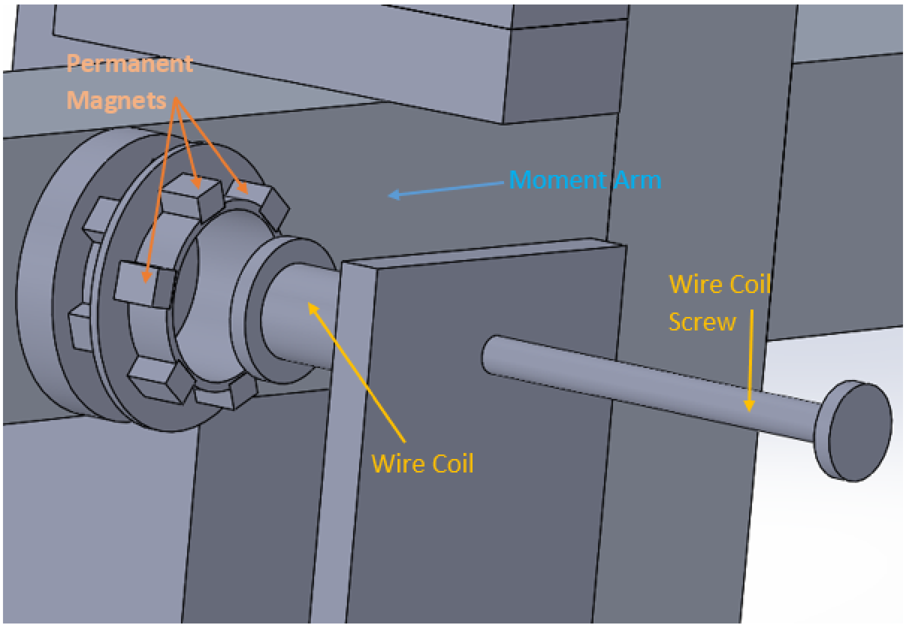

Figure 14: Magnetic Calibration Set Up

7.2.5 Thruster Interface Components

A thruster interface was designed to give ease of thruster attachment, fulfilling requirement TI-10. The interface plate, seen in Figure 15, houses a gas connection and 4 thermocouple connections. By connecting to the thruster interface plate, the wires are routed to the plate in such a manner so that they do not create unknown forces on the system and do not affect the measurement. The 4 thermocouple connections satisfy requirement FI-07, and the gas feedthrough satisfies requirement FI-06.

Component	Vendor	Cost per unit	Number Needed	Total cost	Component details
Thruster Interface					
Thermocouple Connectors	TE Connectivity	15.47	4	61.88	TE Connectivity AMP Connector
Gas Connection Swagelok	Swagelok	15	2	30	0.25" female NPT Hex Coupling
Gas Connector Tube	BuyMetal	9.15	1	9.15	0.25" by 1"

Table 13: Thruster Interface Components

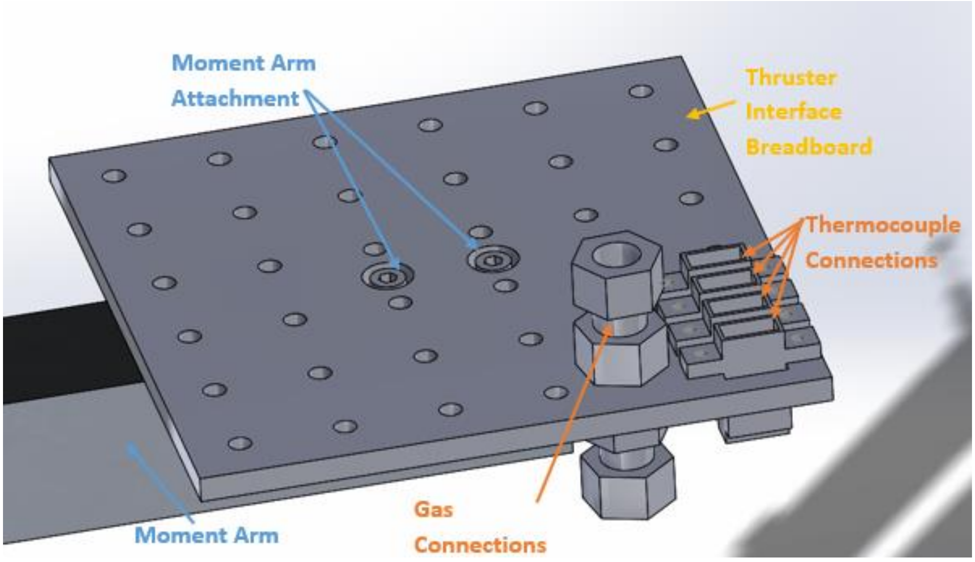

Figure 15: Thruster Interface Components

8 Future Works

The scope of this senior design was to design the thrust stand. The next step would include fabrication and experimentation with the thrust stand. This stand was designed for a PPT, however, it was designed in such a way that it can be modified in the future. PPT's do not generate a lot of thermal runoff, but Hall thrusters do. So, if the thrust stand was to be used for a Hall thruster, thermal shrouding would be needed between the thruster and the stand. In the design, the thruster interface plate is attached with screws so that the plate can be elevated and surrounded in cooling equipment. Additionally, the counterweight system is adjustable to account for different thruster weights.

9 Conclusion

With the constraints of using the 1.5m by 1 m ALPE vacuum chamber, a thrust stand was designed to test the BMP220. A torsional design was selected and mathematical spring mass damper as well as dimensional modelling was performed. A thruster to counterweight ratio for both mass and moment arm of 10:1 was chosen to minimize roll of the system and optimize yaw. The thrust stand was designed with economics in mind, considering how to best utilize COTS to fabricate the design. The thrust stand design includes a thruster interface plate with gas and 4 thermocouple connections, a levelling system, a magnetic calibration system, and a no-contact LVDT for displacement detection. The thrust stand was designed in such a way as to be modifiable in the future for different thrusters. The counterweight mass can be changed to accommodate different thrusters. The Thruster interface plate can elevate to include thermal decoupling of the thrust stand and the thruster.

10 References

[1] J. S. Peter Fortescue, Graham Swinerd, *Spacecraft Systems Engineering*, Fourth. John Wiley and Sons LTD, 2011.

[2] T. E. Markusict, J. E. Jones, and M. D. Cox, “Thrust Stand for Electric Propulsion Performance Evaluation,” *Rev. Sci. Instrum.*, vol. 77, no. 10, 2004.

[3] K. A. Polzin *et al.*, “Performance of a Low-Power Cylindrical Hall Thruster,” *J. Propuls. Power*, vol. 23, no. 4, pp. 886–888, Jul. 2007.

[4] U. Kokal and M. Celik, “Development of a mili-Newton Level Thrust Stand for Thrust Measurements of Electric Propulsion Systems.”

[5] J. E. Polk *et al.*, “Recommended Practices in Thrust Measurements,” *J. Propuls. Power*, vol. 33, no. 3, pp. 539–555, 2013.

[6] A. J. Verbin, “Detailed Design of a Pulsed Plasma Thrust Stand,” 2017.

[7] “Micro-thrust Stand.” [Online]. Available: http://123.57.252.252/Research/Micro-thrust_Stand/. [Accessed: 03-Apr-2019].

11 Appendices

Appendix A: Requirement Verification Matrix

Definitions, Descriptions, and Acronyms

Maturity	
Low	This requirement requires heavy language revision and discussion.
Medium	This requirement is nearly finalized and requires some discussion. Examples include requirements needing language or value discussions & revisions.
High	This requirement is finalized and requires no additional discussion.

Verification Methods	
Inspection	Visual examination of drawings, data, or item using standard quality control methods, w/o special lab procedures or equipment
Demonstration	Operation, adjustment, or reconfiguration of a test article
Analysis	Evaluation of data by generally accepted analytical techniques
Test	Technical means, such as the use of special equipment, instrumentation, or simulation

Requirement ID
Numeral values following prefix are in order of conception, not by significance

Source ID
All requirements must satisfy a parent requirement, otherwise they should not be a requirement.

Acronyms	
OBJ	Objective
SC	Success Criterion
FI	Facility Interface
HS	Handling and Storage
TI	Thruster Interface
FAB	Fabrication
PFM	Performance
TM	Thermal Management

RVM

ID	Maturity	Source ID	Requirement Statement	Verification Method	Comments
System Requirements					
OBJ-01	High	Final Report	Design a thrust stand capable of measuring the true thrust force produced by a pulsed plasma electric propulsion thruster for use in the Aerospace Laboratory for Plasma Experiments	N/A	
OBJ-02	High	Final Report	Design a thrust stand for use as an educational aid in electric propulsion academic research	N/A	
SC-01	High	Final Report	The thrust stand shall measure pendulum arm displacement induced by an EP thruster and convert the displacement to units of force.	N/A	
Facility Interface - Mechanical					
FI-01	High	OBJ-01	The thrust stand shall be able to be contained within the ALPE 1.5-m long, 1-m diameter vacuum chamber	Inspection	
FI-02	High	FI-01	The thrust stand footprint length shall not exceed 30 in	Inspection	Length of the internal 80/20 structure is 31 in.
FI-03	High	FI-01	The thrust stand footprint height shall not exceed 20 in	Inspection	Height of the internal 80/20 structure is 24.5 in.
FI-04	High	FI-01	The thrust stand footprint width shall not exceed 40 in	Inspection	Width of the internal 80/20 structure in the front half of the chamber is 40 in.
FI-05	High	OBJ-01	The thrust stand shall connect to the Aluminum 80/20 structural framing system installed in the ALPE vacuum chamber	Demonstration	
Facility Interface - Power, Signal, and Gas					
FI-06	High	OBJ-01	The thrust stand shall be capable of interfacing with the existing facility power, signal, and gas connections	Demonstration	
FI-07	High	FI-06	Four type K thermocouples shall connect to the thrust stand from the facility	Demonstration	A quad type-K thermocouple feedthrough is available for chamber
Handling and Storage					

HS-08	High	OBJ-01 OBJ-02	The thrust stand shall be easily installed/removed from the ALPE vacuum facility.	Demonstration	Thrust stand must be easily installed and removed with little to no physical challenge by a single person
HS-09	High	HS-08	The thrust stand shall have a weight ≤ 50 lbs	Inspection	OSHEA limit compliance
Thruster Interface					
TI-10	High	OBJ-01 OBJ-02	There shall be a thruster interface designed for easy thruster attachment	Demonstration	
Fabrication					
FAB-11	High	OBJ-01	Thrust stand shall be simple to machine and assemble using WMU machine shop equipment	Demonstration	
FAB-12	High	OBJ-01	The thrust stand and all its components shall utilize low-outgassing materials	Inspection	Low-outgassing materials protect the facility and ensure efficient pump-down to high-vacuum
FAB-13	High	HS-09 FAB-12	The thrust stand structure shall be constructed with Aluminum 6061-T6.	Inspection	
Performance					
PFM-14	High	OBJ-01	The thrust stand shall convert a lateral force into an electrical voltage signal.	Test	The voltage signal will be read by the lab DAQ.
PFM-15	Medium	PFM-14	The thrust stand shall have a sensitivity of 10mV/µN ± 1mV/µN.	Analysis	Ex. 10mV/µN ± 1mV/µN
PFM-16	Medium	PFM-14	The thrust stand shall have a resolution of 1 µN.	Analysis	Ex. In the µN range.
PFM-17	Medium	PFM-14	The thrust stand shall have an accuracy of 10 µN.	Analysis	
PFM-18	Medium	PFM-14	The thrust stand shall have a response time capable of measuring a single impulse from the BMP220.	Analysis	
PFM-19	High	OBJ-01	The thrust stand shall be capable of being precisely levelled to ensure measurement accuracy	Demonstration	
Thermal Management					
TM-20	Medium	OBJ-01	The thrust stand shall be thermally managed to prevent sensitive components from overheating	Test	

Appendix B: Equation Derivations

A pendulum thrust stand can be modelled as a spring mass damper system with the following equation of motion in response to a force F(t).

$$I\ddot{\theta}(t) + c\dot{\theta}(t) + k\theta(t) = F(t)L$$

Where I is the moment of inertia, c is the damping constant, and k is the spring constant. F(t) is the force of the thruster and L is the moment arm from the axis of rotation. To solve for the change in angular position, , as a function of time, the equation is converted to the s domain using the Laplace transform. The angular position as a function of s is solved for then the inverse Laplace transform gives the angular position as a function of time. Below are the Laplace transforms of the angular position and its derivatives.

$$\ddot{\theta}(t) = s^2\theta(s) - s\theta(0) - \dot{\theta}(s)$$

$$\dot{\theta}(t) = s\theta(s) - \theta(0)$$

$$\theta(t) = \theta(s)$$

With an initial position at zero and initial velocity of zero, the Laplace's can be simplified]

$$\dot{\theta}(s) = \theta(0) = 0$$

$$\ddot{\theta}(t) = s^2\theta(s)$$

$$\dot{\theta}(t) = s\theta(s)$$

$$\theta(t) = \theta(s)$$

Also, assuming the Force is an instantaneous step input, which can be calculated from the impulse bit.

$$F(t) = \begin{cases} 0 & t < 0 \\ F(t) = I_{bit} * \delta(t) & t \geq 0 \end{cases}$$

Where $\delta(t)$ is a Dirac Delta function.

$$I\big(s^2\theta(s)\big) + c\big(s\theta(s)\big) + k\big(\theta(s)\big) = \frac{I_{bit}L_T}{s}$$

$$\theta(s)(I(s^2 + cs + k) = \frac{I_{bit}L_T}{s}$$

$$\theta(s) = \frac{I_{bit}L_T}{s(Is^2 + cs + k)} = \frac{\frac{I_{bit}L_T}{I}}{s(s^2 + \frac{c}{I}s + \frac{k}{I})}$$

Defining the natural frequency and the damping ratio, the equation can be written in the two terms.

$$\omega_n = \sqrt{\frac{k}{I}}$$

$$\zeta = \frac{c}{2}\sqrt{\frac{1}{Ik}}$$

$$\theta(s) = \frac{\frac{I_{bit}L_T}{I}}{s(s^2 + 2\zeta\omega_n s + \omega_n{}^2)}$$

Using common inverse Laplace transforms, the angular position as a function of time is found for three different damping cases.

$$\theta(t) = \begin{cases} \frac{I_{bit}L_T}{I\omega_n{}^2}\left(\frac{1}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\sin(\omega_n\sqrt{1-\zeta^2}t)\right) & \zeta < 1\ (underdamped) \\ \frac{I_{bit}L_T}{I\omega_n{}^2}\omega_n t e^{-\omega_n t} & \zeta = 1\ (critically\ damped) \\ \frac{I_{bit}L_T}{I\omega_n{}^2}\left(\frac{1}{2*\sqrt{1-\zeta^2}}\left[e^{-(\zeta-\sqrt{\zeta^2-1}\omega_n t} - e^{-(\zeta+\sqrt{\zeta^2-1}\omega_n t}\right]\right) & \zeta > 1\ (overdamped) \end{cases}$$

Where, L_T is the distance from the thrust generation point to the rotational axis, I_{bit} is the impulse bit of the thruster.

Appendix C: Dimensional Modelling

The following is code from MATLAB used to determine the optimal counterweight moment arm and weight.

```
% Design of a Thrust Stand for Electric Propulsion Devices
% Dimensional Equattions
% Sarah Sokolski and Hannah Watts

clear
close all
clc

%{
Busek BMP-220
mt = 0.5
a = 0.095 m
b =  0.095
Ib = 0.02*10^-3 % impulse bit, N-s
%}
```

Know Values

```
mt = 0.5; % mass of the thruster, kg
a = 0.095; % first footprint dimension of the thruster, m
b = 0.095; % seccond footprint dimension of the thruster,m

lt_vec = 0.3048; % thruster moment arm, chosen for the chamber, set to 30 cm for chamber size
```

Test Values

```
mcw_vec = 0.1:0.1:5; % counterweight mass, from 0.1 to 5 kg in 0.1 kg increments

lcwz_vec = 0:0.01:0.3; % counterweight length in the z direction, m

for i = 1:length(mcw_vec)
    for j = 1:length(lt_vec)
        lt = lt_vec(j);
        mcw = mcw_vec(i);

        lcw = mt*lt/mcw; % counterweight moment arm, from 1 to 5 cm in 1 cm increments

        Iyaw = mt*lt^2+mcw*lcw^2; % Mass moment of inertia in the yaw direction

        Iyaw_mat(i,j) = Iyaw;
        lcw_vec(i,j) = lcw;

        for k = 1:length(lcwz_vec)

            lcwz = lcwz_vec(k);

            It = 1/12*mt*(a^2+b^2); % Mass moment of inertia of the thruster in the roll
direction
            Iroll = It+mcw*lcwz^2;   % Roll moment of inertia of the system
```

```
            I_ratio = Iyaw/Iroll;

            It_mat(i,j,k) = It;
            Iroll_mat(i,j,k) = Iroll;

            I_ratio_mat(i,j,k) = I_ratio;
        end

    end
end

[M1,I1] = min(I_ratio_mat);                % minimum with respect to column: mcw
[M2,I2] = min(min(I_ratio_mat));           % minimum with respect to row: lcw
[M3,I3] = min(min(min(I_ratio_mat)));      % minimum with respect to z: lcwz

I1 = I1(1);
I2 = I2(1);

kmin = I2(1);
jmin = I3(1);
imin = I1(1);

Iratio = M3             % optimum yaw to roll ratio, want to be as small as possible with a
reasonable counterwieght moment arm
lcwz = lcwz_vec(I3)     % counterweight moment arm in z direction for moment ratio
mcw = mcw_vec(I1)       % mass of counterweight at moment ratio
lcw = lcw_vec(I1)       % length of counterweight for moment arm
```

```
Iratio =

    0.1134


lcwz =

     0


mcw =

     5


lcw =

    0.0305
```

Published with MATLAB® R2018a

Appendix D: Component List

Component	Vendor	Cost per unit	Number Needed	Total cost	Component details
Structure					
Aluminium Rectangular tube 10 in	BuyMetal	12.06	1	12.06	1.5" x 3" x 10 " with 0.125" thickness
Aluminium Rectangular tube 18 in	BuyMetal	18.02	1	18.02	1.5" x 3" x 18 " with 0.125" thickness
Aluminium Rectangular tube 12 in	BuyMetal	10.81	1	10.81	1.5" x 3" x 12 " with 0.125" thickness
Aluminium Square Tube 16 in	BuyMetal	14.95	1	14.95	1.5" x 1.5" x 16" with 0.125" thickness
Aluminium Square Tube 3 in	BuyMetal	8.1	1	8.1	1.5" x 1.5" x 3" with 0.125" thickness
Aluminium Square 9.5 in	BuyMetal	16.55	1	16.55	1.5" x 1.5" x 9.5"
Aluminium Plate 0.313" thick	BuyMetal	35.65	1	35.65	5" x 5" x 0.313"
Aluminium Plate 0.75" thick	BuyMetal	83.7	2	167.4	4 x 3 x 0.75"
Aluminium Plate 0.5" thick	BuyMetal	221.13	1	221.13	18 x 20 x 0.5"
M5 x 10 mm screw	Home Depot	0.34	12	4.08	6 for base, 4 for arm, 10 for flexure pivot connection
M5 Nut	Home Depot	0.265	10	2.65	6 for base, 4 for arm
M5 x 50 mm	Home Depot	0.69	2	1.38	2 for base flexure pivot connection
Stepper Motor	Lin Engineering	40.8	3	122.4	4118S-04P
Inclinometer	Analog Devices Inc	112	2	224	Part Number: ADIS16209/PCBZ
Flexure Pivot	Riverhawks Flex Pivot	192	2	384	1" diameter
Counterweight					
Carbon Steel	BuyMetal	7.2	5	36	1" x 1" x 3"
Instrumentation					
NC-LVDT	LORD Sensing Microstrain	425	1	425	LVDT
Calibration System					
Permanent Magnet	AMFMagnets	0.68	12	8.16	
Aluminium Bar 0.5" thick	BuyMetal	4.85	1	4.85	0.5 " x 1"
Thruster Interface					

Thermocouple Connectors	TE Connectivity	15.47	4	61.88	TE Connectivity AMP Connector
Gas Connection Swagelok	Swagelok	15	2	30	0.25" female NPT Hex Coupling
Gas Connector Tube	BuyMetal	9.15	1	9.15	0.25" by 1"
			Total Cost	**1818.22**	

Appendix E: ABET Forms

Form 1
To be completed by student

Assessment of Student Outcome # c
ME 4800

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

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

1. This project involved the design of a: ***system / component / process***
   Description:

   This project involved the design of a system. A thrust stand is a dynamic system including mechanical and electrical components.

2. The **need:**

   The Aerospace Laboratory for Plasma Experiments (ALPE) is a lab on WMU's College of Engineering and Applied Sciences (CEAS) campus that has several electric propulsion thrusters but does not have a way to measure the true thrust force they produce. This is an important characteristic to obtain in researching the devices.

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

   Economic:

   This design was economically constrained by the Undergraduate Excellence Research Award money earned by each team member totaling $2,000.00. This was the only funding for the project, so all expenses could not exceed this amount.

   Environmental:

   ____
   ____
   ______

   Social:

Political:

Ethical:

Health & Safety:

This design was constrained in health and safety by requiring any and all use of the device to be done in a vacuum chamber. Electric propulsion thrusters cannot be used in atmospheric conditions and humans should not be directly exposed to the levels of plasma produced by the thrusters.

Manufacturability:

This design was constrained in manufacturability by requiring all future fabrication and assembly to be able to be completed with the equipment and machinery available at WMU's CEAS campus.

Sustainability:

Others:

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

   No. Thrust stands have already been produced by aerospace organizations and academia.

<u>Form 2</u>
<u>To be completed by student</u>

<u>Assessment of Student Outcome #j</u>
<u>ME 4800</u>

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

Evaluation of student outcome **"<u>A knowledge of contemporary issues</u>"**

1. Why is this project needed now?

    This project is needed for ALPE now because the ability to research, study, and continue work on the electric propulsion devices in the lab is limited in its scope by not having the ability to measure the true thrust generated by the devices.

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

    Both electric propulsion devices and thrust stands are developing technologies. Thrust stands are not available as a commercial product and are still being understood and perfected by industry research. Having this technology available on campus will set WMU apart from other similar research facilities and allow for more thorough research to be done on campus.

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

    This project is not done for a company.

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

    N/A

    Identify the competitors for this type of product and compare the proposed design with the products of the company's competitors.

    N/A

4. How did you address any safety and/or legal issues pertaining to this project? (e.g., OSHA, EPA, Human Factors, etc.)

This design was made to be handled by a single person and meets OSHA's weight limit for lifting.

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

There are no known or foreseeable future standards or regulations that could impact the development of this project.

6. Is there a potential for a new patent in your design? Please document similar patents.

No. Thrust stands have already been produced by aerospace organizations and academia.

Form 3
To be completed by student

Assessment of Student Outcome # h
ME 4800

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

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

1. Is this project useful outside of the United States? Explain why.

   Yes. This project is useful to any country or business outside of the United States investing in electric propulsion research and development.

2. Does your project comply with U.S. and/or international standards or regulations? Which standards are applicable?

   There are no known U.S. or international standards or regulations on thrust stands.

3. Is this project restricted in its application to specific markets or communities? To which markets or communities?

   This project only has value to the electric propulsion community.

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

   N/A

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

Air Quality?

This project has no impact on air quality.

Water Quality?

This project has no impact on water quality.

Food?

This project has no impact on food or food production.

Noise Level?

This project has no impact on noise levels.

Does the project impact:

Human health?

This project has no impact on human health.

Wildlife?

This project has no impact on wildlife.

Vegetation?

This project has no impact on vegetation.

Does this project improve:

Human interaction?

This project does not pertain to human interaction.

Well-being?

This project does not pertain to well-being.

Safety?

This project does not pertain to safety improvements.

Others?

This project improves the students' ability to research and develop electric propulsion devices at WMU.

<u>Form 4</u>
<u>To be completed by student</u>

<u>Assessment of Student Outcome # i</u>
<u>ME 4800</u>

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

Your responses will be used in the Evaluation of student outcome **"<u>A recognition of the need for, and ability to engage in life-long learning.</u>"**

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

<u>ME 4800</u>
<u>Mechanical and Aerospace Engineering Design Project</u>

<u>For each team member:</u>
NAME: SARAH SOKOLSKI

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

    In order to execute my responsibilities on the project, I needed time management skills, technical writing skills, public presentation skills, and understanding of control systems and dynamics, and CAD skills.

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

    All of the above skills were acquired and improved upon throughout the pursuit of this degree. These skills were also utilized and improved upon in the Western Aerospace Launch Initiative (WALI) student organization that I participate in.

<u>Form 4</u>
<u>To be completed by student</u>

<u>Assessment of Student Outcome # i</u>
<u>ME 4800</u>

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

Your responses will be used in the Evaluation of student outcome **"<u>A recognition of the need for, and ability to engage in life-long learning.</u>"**

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

<u>ME 4800</u>
<u>Mechanical and Aerospace Engineering Design Project</u>

<u>For each team member:</u>
NAME: HANNAH WATTS

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

    The skills needed for this project included CAD modelling skills (SolidWorks), proficient coding abilities in MatLab, and a fundamental knowledge of vacuum chambers and vacuum science.

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

    I acquired and have improved upon these skills throughout the classes I've taken at WMU, in my participation in the WALI student organization, and in my participation in the research being done in ALPE.