10/2/2020

EML4551-2

Team 512: Lockheed Martin – Low – Cost HOTAS Design for Pilot Training Devices

Robert Blount, Connor Chuppe, Robert Craig, Patrick Dixon

FAMU-FSU College of Engineering 2525 Pottsdamer St. Tallahassee, FL. 32310

Abstract

Lockheed Martin is in need of a low-cost Hands-On Throttle and Stick (HOTAS) system to support the Pilot Training Devices (PTD) product line. The addition of buttons to the throttle and stick is what turns a regular throttle and stick into a HOTAS. The product will replicate the throttle control assembly and control stick of fighter aircraft. It is desired to have one common design that supports multiple aircraft through an interchangeable outer grip. These grips will be aircraft specific to allow pilots of different aircraft to train on the same simulator. This project will include the electrical and mechanical aspects of the HOTAS devices. The device must output the appropriate signals in response to stick and throttle position and pressing of buttons. The stick control shall provide progressive resistance in proportion to the speed and angle of maneuver of the aircraft.

Acknowledgement

We want to thank our sponsor Mr. Andrew Filiault at Lockheed Martin. His help has been two-fold as he is out sponsor or the project, but he also has been a mentor to us. We were very fortunate to be connected with a former student of the FAMU-FSU College of Engineering. He has been able to give us insights on not only our project, but on the entire design process. His support is invaluable.

We want to thank our adviser Dr. Hollis for his insights into our project. He has worked with other projects sponsored by Lockheed Martin, so he was able to help us ask the right questions to our sponsor

We want to thank Dr. McConomy for giving us the project in the first place. He is very busy because he is the director of the entire Senior Design program. But he is still able to take time out of his day to help us when we need clarification on certain aspects of our project.

We would also like to thank the teaching assistants for this course, Melanie Munroe and Joshua Jones. Their help when it comes to assignments has been greatly appreciated. Whenever we ask for help, they have responded in an expeditious fashion. All of these wonderful people have helped our group to do our best work.

Table of Contents

List of Tables

List of Figures

Figure 1. The figure below shows the different systems and minor functions of our project in a flow chart.

Notation

COTS	Commercially off the Shelf
HOTAS	Hands-On Throttle and Stick

Chapter One: EML 4551C

1.1 Project Scope

Project Description

The objective of this project is to create a low-cost Hand-On Throttle and Stick (HOTAS) system to support the Pilot Training Devices (PTD) product line. The product will replicate the throttle control assembly and control stick of various fighter aircrafts.

Motivation

To get the competition to sell to Lockheed cheaper or to be able to make HOTAS in house at a low cost with comparable functionality to their current solutions.

Key Goals

1. Create a low fidelity HOTAS with reasonable manufacturing costs, and repairability
2. Be able to function with Prepar3D software (Lockheed Martin simulation software)
3. FAMU-FSU to design circuit board with micro controller to encompass all functionality.

4. Shall provide the same functionality as current models used (bugeye F35 HOTAS, Wraith systems F35 HOTAS)
5. Shall be able to be used for desktop training
6. Be able to communicate with computer via standard IO

Markets

The primary market:

Lockheed Martin - directly invested financially and looking to apply this technology internally in their training programs. For use with multiple vehicle designs and desktop simulation software.

Secondary markets:

Military Service branches - The military applications of this product if released could reduce overall costs for training pilots and their required products in multiple scenarios.

Industrial applications – where these HOTAS units could be integrated into training and cockpits for large Industrial equipment, such as cranes, skid steers, and other specialized vehicles.

Gaming and E-sports – Could potentially see product usage and enter a competitive market of other controllers and units in the low-fidelity market, while increasing gaining usage in aircraft and spacecraft simulators.

Assumptions

Our assumptions of the project began with interpretation of the project statement, followed by meeting with Andrew our Lockheed Martin Contact. From this meeting we were able to get a basis on what our intended project goals, needs, and assumptions were. These assumptions are the ones we have made, the HOTAS is being designed for Lockheed Martin use only, and it will primarily be for desktop vehicle training simulations. The HOTAS itself will be crafted from low cost materials, and potentially be mounted in use. The Power of the HOTAS will be provided by connected desktop, with software being purchased or provided by the sponsor. The hardware for the HOTAS shall be commercially off the shelf products, and we will be designing internal circuitry to encompass functionality. The HOTAS is assumed to use an interchangeable outer grip for various vehicles. The design and creation will cover all electrical and mechanical aspects of a functional HOTAS.

Stakeholders

The stakeholders of our project include our own group members in T512 as we are directly affected by the performance of this project, Dr. Shayne McConomy is our current technical instructor for senior design, as well as our direct advisement, his investment in both time and service implies he is a large stakeholder. The Pilots and end users who use products similar to ours will be affected by our project's success or failure. Lockheed Martin is the direct company sponsor of our project and Andrew Filiault, an employee of the company as a mechanical engineer, is also an investor in both his time and service similar to Dr. McConomy, implying he is also a large stakeholder in this project. Dr. Patrick Hollis is our current faculty advisor on this project and will be invested in time and work effort in completing this project.

1.2 Customer Needs

For our Customer Needs we decided to first create a document involving questions for our Lockheed Martin sponsor to answer. We were able to meet with Mr. Andrew

Filiault to discuss the questions in greater detail via a zoom teleconference. Based on the questions posed we were able to create a list of interpreted needs from the statements given by Mr. Filiault. Each interpreted need will be formulated into an unambiguous, verifiable target with an associated value given as a measurement. Table 1 below shows the documentation of questions, statements, and the interpreted needs.

Table 1: Customer Needs interactions

Questions	**Customer Statements**	**Interpreted need**
How many units are expected to be produced?	If all goes well, ~1,000 units and possibly more.	Design needs to be easily reparable.
How will the unit be implemented into your system?	It'll be mounted on a desktop and used in software training for a variety of military vehicles	Design needs to fit variety of military vehicle handles.
What is considered Low Cost?	Current models are around $8,000	Final Design needs to be under $4,000
Are we taking an existing design to modify or completely making a new design?	Building from the ground up	Create an original design
Are we making our own grips or using grips from existing aircraft?	Creating your own grip	Grip can be any design as long as its functional

Should we make a base, or will it be connected to an existing simulator?	You will need to make a base	HOTAS will be used on a desktop simulator
How many buttons and switches etc., what kind of functionality and accuracy is intended?	Reference current models. Design will be used for low fidelity training.	HOTAS needs to have the same functionality as most current models
What kind of software will be used?	Prepar3d is software used.	Needs to be able to integrate with software.
What are the expectations for the feedback?	Device should provide resistance dependent on relative speed.	HOTAS needs to provide resistance proportional to the simulated speed of the military vehicle

While keeping the customer statements in mind we were able to determine our most important needs. These are Function, Cost, Fit, Lifespan, and Form. These needs were specified in order of importance by the client, with interpreted needs being either given or being discussed in detail. Each need has an intended overall purpose, Function serving as the main need with it being considered successful, if the overall product and components work as intended while under daily usage without noticeable failure. The cost of the overall unit being the next target of concern, we will attempt to reduce the cost of each sub-system posed to appropriately reduce cost. This has been chosen as what to do, as Lockheed's current commercial solutions are priced at $8,000, and $16,000 respectively with Low and Medium fidelity solutions. This also ties into lifespan of the product because if the sub-systems of the HOTAS fail but the components are cheap enough to replace, this will extend the overall lifespan of the product. Also, since the project is more centered around function, form and fit will be of lesser importance, meaning that as long as the HOTAS functions with the software it does not necessarily matter if it is the best feeling or looking HOTAS.

1.3 Functional Decomposition

For our functional decomposition, we analyzed our product, and broke it down into its fundamental systems and functions. From our design, we narrowed the systems down to three main groups, that broke into sub-systems from those groups. The three main systems of our product are Ergonomics, Electronics and Mechanical. We developed a flow chart as well as comparison calculation tables to show and numerically rank the importance of each system and function within the overall design. Figure 1 below is an overview of our product's functional decomposition in a flow chart form, from System to sub-system, then functions directly tied to the needs of our customers. This shows the basis of each function and which system it will be categorized under.

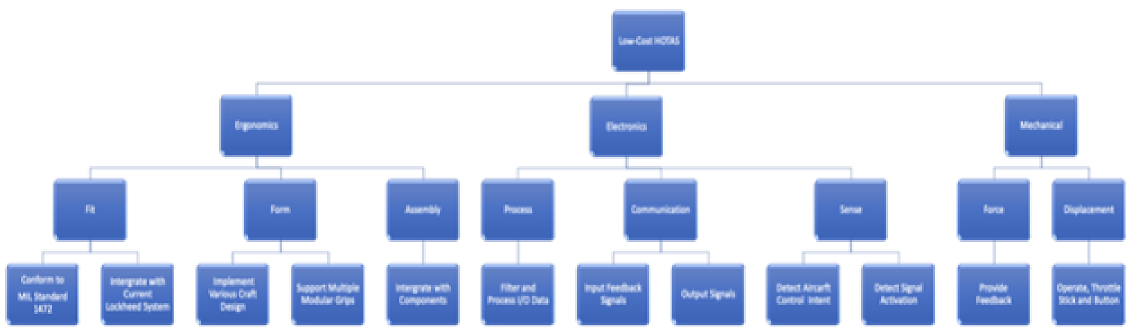


Figure 1. Functional Decomposition Flowchart.

Our Minor Functions were found by breaking down the HOTAS into the simplest tasks, and whether or not they could be used to validate a target and metric. Given that, conforming to MIL standard 1472 is not necessarily how a HOTAS functions, however it is a function of Human Engineering, which falls into the scope, or functions, of the project. The same goes for Implementing Various Craft Designs, integrate with Current Lockheed System and Support Multiple Modular Grips, although these do not explain how a HOTAS directly functions, they are specifically outlined to be included in our project and can be directly applied to hit a target or metric.

For the subsystem of Sense, Detect Aircraft control Intent and Detect Signal Activation are similar but Detecting Aircraft Control Intent deals with the pitch, yaw and roll of the aircraft, whereas Signal Activation deals with button activation in a 0 or 1 capacity, and both are direct functions needed for a HOTAS to operate. The electronic subsystem contains the various ways the HOTAS senses, processes and communicates the information with whatever it is paired with. These are the most basic functions of how the movement of the stick is turned into flight control surfaces movements, or how button depression corresponds to the function it is intended to produce. Under Mechanical, there is Force and Displacement since these two are physical aspects of the HOTAS. Force is further broken down into Provide Feedback and is giving some sort of resistance or feel to the user. This uses interpreted speed, AOA (Angle of Attack), angle of bank etc. to do this, all as inputs from external software. Displacement is further broken down into Operate Throttle and Stick and deals with the throttle's physical ability to slide or rotate, and the stick being able to rotate.

The first of the three tables provided lists each of the three main systems in the first column. The next columns house the subsystems then tied to their respective function or functions. This table shows a comparison as to which functions can target more than one sub-system of the overall project. This gives us a general basis as to which functions we should place more emphasis on. The numbers indicate either a "1" for a yes it applies and effects that system, and a "0" otherwise.

System	Major System	Minor System	Fuction	Fit	Form	Assembly	Process	Communicate	Sense	Force	Displace	Provide Feedback	Row Total
HOTAS	Ergonomics	Fit	Conform to MIL standard 1472	1	1	0	0	0	0	1	0	0	3
			Integrate with Current Lockheed System	1	1	1	0	1	1	0	0	0	5
		Form	Support Multiple Modular Grips	1	1	1	0	0	0	1	0	0	4
			Implement Various Craft Designs	0	1	0	0	0	0	1	1	1	4
				0	0	0	0	0	0	0	0	0	0
		Assembly	Integrate with components	0	1	1	0	0	0	0	0	0	2
	Electronics	Process	Filter and Process I/O Data	0	0	0	1	1	1	0	0	1	4
		Communication	Input Feedback Signals	0	0	1	1	1	1	0	0	0	4
			Output Signals	0	1	1	0	1	0	0	0	0	3
		Sense	Detect Aircraft Control Intent	0	0	0	0	0	1	0	1	0	2
			Detect Signal Activation	0	0	1	0	0	1	0	1	0	3
	Mechanical	Force	Provide Feedback	0	1	1	0	0	0	1	1	1	5
		Displacement	Operate Throttle, Stick, and Buttons	0	1	1	0	1	1	1	1	1	7

Table 2. Basic Functional Decomposition Calculation.

To further explain, Conform to MIL standard 1472 has a one for Fit, Form and Force meaning this Function could be represented under any of these three subsystems. From this table we interpreted that Operate Throttle, Stick and Buttons, Provide Feedback and Integrate with Current Lockheed System could be fit into the greatest number of subsystems.

In the second table, each of the individual functions is listed in the first column, and the values for the rankings of the functions against each other are listed in the following columns. Items were ranked on a 1,3,5,7, and 9 scale and their reciprocals as well across the identity, each shows a more significant contribution to success with 9 being total domination of contribution. The reciprocals show a lesser importance than the comparison item varying by the 1,3,5,7, and 9 integers. The sum is then a total of the columns, with a lower total relating to a more important function. We use this sum to normalize the data and create table 4, this is our normalized comparison matrix. Table 4 is shown below.

Function	Conform to MIL standard 1472	Integrate with Current Lockheed System	Support Multiple Modular Grips	Implement Various Craft Designs	Integrate with components	Filter and Process I/O Data	Input Feedback Signals	Output Signals	Detect Aircraft Control Intent	Detect Signal Activation	Provide Feedback	Operate Throttle, Stick, and Buttons
Conform to MIL standard 1472	1	5	3	7	1	0.11	0.14	0.14	0.11	0.14	9	0.33
Integrate with Current Lockheed System	0.20	1	3	5	1	0.20	0.33	0.33	0.11	0.33	5	0.20
Support Multiple Modular Grips	0.33	0.33	1	1	0.33	0.14	0.14	0.14	0.11	0.14	3	0.14
Implement Various Craft Designs	0.14	0.20	1	1	0.20	0.14	0.14	0.14	0.14	0.14	0.33	0.11
Integrate with components	1	1	3	5	1	0.20	0.33	0.33	0.11	0.20	0.20	0.20
Filter and Process I/O Data	9	5	7	7	5	1	7	7	1	1	5	1
Input Feedback Signals	7	3	7	7	3	0.14	1	1	0.20	0.20	3.00	0.20
Output Signals	7	3	7	7	3	0.14	1	1	0.20	0.20	3.00	0.20
Detect Aircraft Control Intent	9	9	9	7	9	1	5	5	1	5	7	1
Detect Signal Activation	7	3	7	7	5	1	5	5	0.200	1	0.14	3
Provide Feedback	0.11	0.20	0.33	3	5	0.20	0.33	0.33	0.14	7	1	0.33
Operate Throttle, Stick, and Buttons	3	5	7	9	5	1	5	5	1	0.33	3	1
Sum Total	44.787	35.733	55.333	66.000	38.533	5.283	25.429	25.429	4.330	15.695	39.676	7.724

Table 3. Pairwise Comparison Matrix Evaluation of Minor Functions

Table 4 shown below is mathematically showing weights of each function based on values assigned in the second table. These weighted values show the highest rated functions mathematically, and which are most important to the project. The highest rated items are highlighted in green under the weighted total percentile column. Next a consistency check was performed, showing that we have not biased our information. The consistency info and important values are shown in yellow and explained below the table.

Function	Conform to MIL standard 1472	Integrate with Current Lockheed System	Support Multiple Modular Grips	Implement Various Craft Designs	Integrate with components	Filter and Process I/O Data	Input Feedback Signals	Output Signals	Detect Aircraft Control Intent	Detect Signal Activation	Provide Feedback	Operate Throttle, Stick, and Buttons	Weighted Totals	Weighted Totals Percentile	Consistency Vector	Average Consistency	N Value	Random index Value for n = 12
Conform to MIL standard 1472	0.0223	0.1399	0.0542	0.1061	0.0260	0.0210	0.0056	0.0056	0.0257	0.0091	0.2268	0.0432	0.0571	5.71	0.7231	0.9864	12	1.54
Integrate with Current Lockheed System	0.0045	0.0280	0.0542	0.0758	0.0260	0.0379	0.0131	0.0131	0.0257	0.0212	0.1260	0.0259	0.0376	3.76	0.8545			
Support Multiple Modular Grips	0.0074	0.0093	0.0181	0.0152	0.0087	0.0270	0.0056	0.0056	0.0257	0.0091	0.0756	0.0185	0.0188	1.88	1.1042			
Implement Various Craft Designs	0.0032	0.0056	0.0181	0.0152	0.0052	0.0270	0.0056	0.0056	0.0330	0.0091	0.0084	0.0144	0.0125	1.25	1.3337	Consistency Index	Consistency Ratio	these values are < 0.10 making
Integrate with components	0.0223	0.0280	0.0542	0.0758	0.0260	0.0379	0.0131	0.0131	0.0257	0.0127	0.0050	0.0259	0.0283	2.83	0.8440	-1.0012	-0.6502	the comparisson consistent
Filter and Process I/O Data	0.2009	0.1399	0.1265	0.1061	0.1298	0.1893	0.2753	0.2753	0.2309	0.0637	0.1260	0.1295	0.1661	16.61	1.0485			
Input Feedback Signals	0.1563	0.0840	0.1265	0.1061	0.0779	0.0270	0.0393	0.0393	0.0462	0.0127	0.0756	0.0259	0.0681	6.81	0.6968			
Output Signals	0.1563	0.0840	0.1265	0.1061	0.0779	0.0270	0.0393	0.0393	0.0462	0.0127	0.0756	0.0259	0.0681	6.81	0.6968			
Detect Aircraft Control Intent	0.2009	0.2519	0.1627	0.1061	0.2336	0.1893	0.1966	0.1966	0.2309	0.3186	0.1764	0.1295	0.1994	19.94	1.0554			
Detect Signal Activation	0.1563	0.0840	0.1265	0.1061	0.1298	0.1893	0.1966	0.1966	0.0462	0.0637	0.0036	0.3888	0.1406	14.06	1.0610			
Provide Feedback	0.0025	0.0056	0.0060	0.0455	0.1298	0.0379	0.0131	0.0131	0.0330	0.4460	0.0252	0.0432	0.0667	6.67	1.3436			
Operate Throttle, Stick, and Buttons	0.0670	0.1399	0.1265	0.1364	0.1298	0.1893	0.1966	0.1966	0.2309	0.0212	0.0756	0.1295	0.1366	13.66	1.0748			
Sum Total	1	1	1	1	1	1	1	1	1	1	1	1	1	100				

Table 4. Normalized Comparison Matrix

Highlighted above are the four most important functions pertaining to our project. Detecting Aircraft Control Intent had a weighted percent total of 19.94%, Filter and Process I/O Data had a weighted percent total of 16.61%, Detect Signal Activation and Operate Throttle, Stick and Buttons had a total of 14.06% and 13.66% respectively. While these four functions were determined to be the most important, factors such as bias could be presented in the table and therefore all of these functions will still be considered important when going through the design process with a slightly greater emphasis being placed on these four functions. The consistency data has an average consistency of 0.9864 shortened to 4 decimal places, with an N value of 12. This yields a value of 1.54 for the random index from lookup table. From these a consistency index of –1.0012 is determined, with a consistency ratio of –0.6502. Because these values are less than 0.10 the comparison is considered consistent.

1.4 Target and Metrics

Our targets and metrics were determined and described below for each function of our project, as well as other needs that were not directly stated as functions but became important targets and metrics. There is a brief discussion of every target and metric as to how we have arrived at those particular values as well as some examples of testing validation for each target after prototype completion. These targets and metrics came from functions such as the MIL standard 1472 and implementing with various craft design, as well as using benchmark comparisons from existing HOTAS units, or directly from our sponsor's need statements. The methods for validation were determined by picking the most practical way to test if our finished product will satisfy the criteria we have specified in a physical or digital manner, each tool we will use to test will be discussed briefly after the targets and metrics main section, where each method of testing is briefly described. A discussion of our mission critical targets and metrics is shown below followed by a table with the mission critical targets and metrics. Our list and full catalog of targets and metrics is shown in the appendix in Table 6.

Our mission critical targets and metrics described below start with Conforming to MIL standard 1472, this particular one is based on the creation of a device that will be used in military practice, it also leads into the targets and metrics for many other functions we have used with direct values for targets. The second mission critical target and metric is related to Integrating with the current Lockheed Martin system, this is a success or failure scenario based on if it works or not, making it vital for success. Implementing with various craft designs lead to the next mission critical statement, where it is necessary to have the available signals to implement a variety of crafts depending on electrical component orientation differences with multiple aircrafts. The next target and metric were derived from the filter and processing I/O data function, where this is needed to complete the overall goals of the HOTAS unit. Our output signals function was responsible for the next set, where it is considered mission critical to be able to control the aircraft and connect to any external PC. The next two functions share similar Target and Metrics, with the target and metric being related to input latency, however the functions being related to component buttons in one case for signal activation, and the other being related to the direct use of Throttle, and stick basic functionality (engine speed, pitch, roll, and yaw). Our final sets of targets and metrics are related to the mechanical functionality of the overall components of the throttle, stick and various button components.

Critical Targets and Metrics		
Function	**Target**	**Metric**
Conform to MIL standard 1472	Fits 95% of aviators	Length, Diameter, Surface Area of throttle & stick

Integrate with Current Lockheed System	Yes	It works with the system
Implement with Various Craft Design	55 separate signals	Number of available signals
Filter and Process I/O Data	Filter noise, process data into appropriate signal type, fast 0ms	Take in data input and output
Output Signals	Transfer ≤ 5Gbps of data to Prepar3d	Transfer processed data through Output device to computer software
	≤ 10Gbps @ 250 MHz between throttle and stick units	Data transfer size and rate
Detect Aircraft Control Intent	< 20 milli seconds	Input latency
Detect Signal Activation	< 20 milli seconds	Input latency
Operate Throttle, Stick and Buttons	Button can be depressed	Measure force required to depress button
	± 35 degrees for stick rotation	Angle of stick

	Throttle travels 6 " or rotates 65°	Distance throttle travels or angle of throttle

Table 5. Critical Targets and Metrics

<u>Conform to MIL standard 1472</u>

Metric: Length, Diameter, Surface Area of throttle & stick

Target: Fits 95% of aviators

The Metric above is needed for our project as it in direct application in military design and directly correlates to a very large variety of topics including forces, lengths, general sizes and shapes, and all of their dimensions. The Mil-Standard 1472 is a document that pertains directly to human factors engineering and was created by the military with testing to determine the amount of their users in a 95% range that have specific metrics and ranges for their targets based on what these percentages of people can accomplish. Many of the standards discussed in the Mil standard document give specific values that can be validated and benchmarked against when designing many of our base components.

Some examples of this include button pressure required to activate, the size and surface area of an individual's hands that can be applied to making appropriate grips and handles for devices such as our throttle and stick assemblies.

When using this metric, to validate our target we will use the given metric standard from the document and take a measurement to show that it is within the tolerance target.

Integrate with Current Lockheed System

Metric: It works with the system

Target: Yes

This metric and target were chosen as a requirement from our project sponsor, the reasoning is that using their in-house software and the ability to connect to it is either going to marked as success or failure, in example with the system connecting and working with their software prepar3d if we have connection and can operate the software systems appropriately, we have success. If the software cannot be used with the hardware we create, then it is a failure. This leads to the choice of having our target as a yes for success. We will validate this by attempting to use our hardware with the Lockheed martin software prepar3d, and getting a result of success or failure, yes or no. If no/failure we must iterate to make it a success.

Implement with Various Craft Design

Metric: Number of available signals

Target: 55 separate signals

The base of our throttle and stick will have the capability to carry signals from the buttons and components to the computer. The wraith systems F-35 HOTAS unit has a total of 55 button functionalities which means 55 separate signals. We assume that the F-35 will have the most functionalities out of all of the other models of aircraft that could be implemented with our system created. The choice of having at least 55 again is from the number of operable controls located on an F-35 HOTAS from either of the two commercial products that Lockheed currently purchases to use. In addition, the basic functions of throttle, pitch, roll, and yaw will always be available. To validate this, we will first check on other aircraft that may be used in simulation by Lockheed Martin and validate their number of buttons and functions. Next, we will be able to physically and digitally determine the validity of this target by appropriately specifying electronic hardware components with the amount of available signals, as well as confirming that we have that number of signals operating through our processing and communications through a software program such as Arduino Ide.

Support Multiple Modular Grips

Metric 1: Length of mounting section for the stick

Target 1: 1”-2"

Metric 2: Major diameter and threading of mounting section for the stick

Target 2: Variable per each stick

Metric 3: Pitch of the mounting threads for the stick

Target 3: ¼-20

These three metrics and targets were created to specify our mounting points target for size including length, constraints for basic usage, and constraints for being able to use multiple aircrafts physical grips in a modular manner. The length metric and target are based on an assumed form factor, to be small enough to fit under/inside of each stick without changing the fidelity of the overall system. We will use the target of 1-2 inches in generating multiple design during our concept generation process, this will be validated by checking various sticks inner diameter dimensions as well as their clearances for wires/cables.

The second target and metric being major diameter and pitch of mounting section again is to constrain us to making a system that is completely modular in fashion. Where we may have the ability to mount a new grip/stick with the ability to create a small component like an adapter to change to a variety of diameters and pitches. This will be validated by being able to switch between at least two different sticks and grips with ease, on both the throttle and the stick side of the HOTAS.

The third target and metric are more of a specification on our part to have a standard for all the units to be able to attach onto. We chose one of the most common diameters and pitches being a ¼"-20. This was an effort to allow the creation of modularity by specifying one side of an attachment point for the stick and throttle units if they need an adapter or not is currently not designed or chosen. We will validate this by looking at the specific unit and size-pitch chosen for the final design.

<u>Integrate Buttons Within Specified Tolerances</u>

Metric: Distance button can be displaced

Target: ±0.078-0.25in (2-6mm)

This target and metric are specified from the internal MIL Standard 1472, where the minimum and maximum button displacements are specified. These became our target tolerances as 2-6mm, we will validate this target by specifying components within that range of motion and then physically measuring to assure validity.

Filter and Process I/O Data

Metric: Take in data input and output

Target: Filter noise, process data into appropriate signal type, fast 0ms

This metric is based on the ability to import and transfer data to its appropriate location at its most basic, assuming that the data does not require processing. However, our target is to import the data, filter the noise of the received signal if appropriate, process the data into its appropriate type. In example from analog to digital signal, with as close as we can get to 0ms response as possible. This value was chosen because the lower each basic component's operating time is the faster the whole system can run. We will validate this by coding the micro controller appropriately with the correct number of items being passed and processed where appropriate. We can further validate the end component of the target by determining the time to process any given set of inputs and outputs of data at a digital level using software.

Input Feedback Signals

Metric: Receive data through I/O to process from computer software

Target: Receive signal for AOA, and craft speed to send for processing into feedback

This metric and target are in direct response to the feedback system that Lockheed martin would like us to create. This portion is the feedback loop to our HOTAS controller system. This will be able to receive signal from an I/O on the HOTAS to send for processing into a valid feedback response for the user. Our target is to receive the Angle of Attack of the craft as well as the velocity to then send to the micro controller for processing. This allows us to alter or command a signal for variable or constant force feedback to be applied if they (Lockheed Martin Pilots) determine that they would like constant feedback instead of variable, as fly-by-wire planes have constant force feedback, not variable which would be more likened to an older all mechanical aircraft. We will validate this digitally by getting these signals to come from the software and being able to read them and process them, as well as measuring the force output by our Stick unit with a spring scale.

Output Signals

Metric 1: Transfer processed data through Output device to computer software

Target 1: Transfer ≤ 5Gbps of data to Prepar3d

Metric 2: Data transfer size and rate

Target 2: ≤ 10Gbps @ 250 MHz between throttle and stick units

These two targets and metric have been specified for outputting signals because they deal with the amount of data that can be sent to the Lockheed Martin software and the speed at which it can be sent. The target for each of two are based upon likely choices for data transfer components, such as USB 3.0 and Cat6 ethernet cables. With the ability to validate these being based on amount of data that needs to be transferred once processed and the physical components being chosen supporting these rates.

<u>Detect Aircraft Control Intent</u>

Metric: Input latency

Target: < 20 milli seconds

<u>Detect Signal Activation</u>

Metric: Input latency

Target: < 20 milli seconds

For both of the targets and metrics above relating to detection, they are for similar tasks but within different components of the overall system. The metric chosen is input latency for the controls, what this refers to is the time between moving the stick and the response of the software to said input, and activating a button and the time for the software to respond. Our target of < 20 ms for both of these two is based on most modern gaming controllers considered low fidelity having a response time much less than 20 ms. In example Xbox and PlayStation controllers, these values will be determined and validated by using digital measuring devices attached to the end of our HOTAS when powered, such that we do not compound latency within the PC system, or screen chosen. This testing will be done by moving the stick or pressing a button and timing the response of the signal to leave the HOTAS after processed, before it moves into the PC and software, which will increase latency significantly.

Provide Feedback

Metric: Provide an actuator force

Target: 1.12 ± 0.450 lbs. (5±2N) of force

According to Mil-standard 1472, an isotonic joystick that has 2 degrees of freedom should provide between 3.3N and 8.9 N of resistance to the user. Since this is a low-fidelity HOTAS unit, we decided to design towards the lower limit of the standard. In order to validate this function, we will use a scale measure the force that the stick outputs. The torque that the actuator will impart will be used with the length of the stick in order to estimate the force that the user will feel from the actuator.

Operate Throttle, Stick and Buttons

Metric 1: Measure force required to depress button

Target 1: 0.629lbs-2.47lbs (2.8N-11N) of force

Metric 2: Angle of stick

Target 2: ± 35 degrees for stick rotation

Metric 3: Distance throttle travels or angle of throttle

Target 3: Throttle travels 6 inches (15.24cm) or rotates 65 degrees

This function consists of three targets and metrics corresponding to the physical movement for the throttle and stick. These targets and metrics are critical to the success of the project because if the stick and throttle do not displace, there will be no signals being sent to the software which means you wouldn't be able to control the pitch, roll and yaw of the aircraft or the engines power output. The first target is the amount of force required to move the stick from the neutral position. In order to validate this, we will use a device such as spring scale to attached to the stick to determine the minimum force required to move it. The second target is the degrees of rotation the stick can move about the x and y axis, essentially the movement of the stick forwards, backwards, and side to side. This can be measured via a protractor to determine the positive, negative, and total angle of movement of the stick from neutral, as well as being a design specification when modeling. The last target is the throttles displacement when moved from idle to full throttle. This distance will be measured via a ruler or a protractor depending on how we choose to design the throttle. The way in which we arrived at these targets and metrics is by examining a similar low fidelity stick and throttle to get the displacement of the throttle and stick. From there we were able to adjust the values of the competitor to fit the needs of our scope. As far as the force required to move the stick, we picked the range of values from the MIL standard 1472 that pertained to the forces required to move a joystick.

Targets & Metrics not Listed as Functions

Metric: Cost in $$

Target: < $4000 to manufacture

The target was determined from what our sponsor directly told us the cost needed to be under for total manufacturing. Given that the project description is a low-cost HOTAS, this target will be a high priority. We will validate this target and metric by adding up the total cost to manufacture the HOTAS and compare it to the target value to determine if we were under or over.

Metric: Weight

Target: 10-15 lbs.

The weight target for our HOTAS are based off industry benchmarks including a variety of thrust master HOTAS unit's shipping weights. In speaking with our sponsor and researching, one of the concerns of most end users for a HOTAS is that it is too lightweight, and therefore moves around on the desktop during normal and extreme operations. We believe that this metric and target being present can allow for a greater fidelity of the overall system while allowing for potential to be more robust in design. We will validate this by physically weighing the HOTAS when it is complete, within certain tolerances to account for packaging in the future.

Metric: Durability

Target: Can be dropped from a height of 29" ± 1" at any orientation without mechanical failure more than 50 times.

Pilot Trainees will be using the HOTAS on a desktop computer and being that the computer system would be placed on a desk, the average desk height is 29 inches. Our HOTAS would need to be capable of consistently functioning after falling off the desk from sliding, due to over applied force, and or accidental misuse. This target will be validated by repeatedly throwing a completed unit prototype off of a desk at least 50 times. This will be validated likely last or not at all depending on overall cost to manufacture one unit.

Metric: Component Lifetime

Target: At least 2 Years

Component lifetime is the lifetime of specific electronic components on the unit. This target is important because theoretically we could have a button fail on the unit and replace that button rather than Lockheed having to throw away the entire unit and buy another one. Given the length of the project, we will not be able to wait two years to see if all of the components would break, however we can simulate this by using various components and a certain number of cycles to roughly estimate how long the individual component will last. In order to validate this, we will look at the off the shelf component life cycles, and compare this to the average number of uses of each component during a known testing time limit, from testing the HOTAS and recording how many times each component is used per flight to roughly approximate how many times each component will be cycled in a year, using a 40 hour per week use model. If the component is cycled less than the given life cycle from the manufacturer over the course of two years, then we will have successfully validated our target.

Metric: Product Lifetime

Target: At least 5 years

The sponsor specified that the product should last for at least 5 years. This refers to the framework of the product. It needs to be able to withstand the average forces imparted by the user over this time period. In order to validate this, we would need to select a material that has a fatigue strength higher than the average stress from the user after a number of cycles needed to last for 5 years. For this target we would validate again using basic testing and mathematical calculation.

Testing Tools discussion:

The tools that we will need to measure and validate our targets are things such as a spring scale which will help us to determine the amount of force required to move the component we are measuring. We will also use this for torque validation with the addition of multiplying the force value by the length of the object that has the force being applied to it. A basic ruler, or tape measure, and a protractor will be used to measure the distances and degrees of rotation of the stick and throttle travel, as well as things such as button displacement, the stick and throttle design and the distance the HOTAS will be dropped from. For measuring signal activation, we will use a high-speed camera along with a multimeter to capture the time it takes for a signal to appear on the multimeter after the button has been depressed. In order to measure the data transfer rates, software will be used to measure and ensure the rate of transfer is within the specified values for our unit. Any other tools and methods for validation were discussed above in each respective target and functions section.

1.5 Concept Generation

In coming up with 100 concepts for our low-cost Hands-on Throttle and Stick, the first 50 concepts shown in the table came from a morphological chart. The chart had our various subsystems listed along the top, and below each subsystem we filled in an arbitrary number of concepts that fit that subsystem. Once this was done, we went across each row and picked one idea from each column to combine into one concept. Biomimicry was used to generate a few concepts, we used ideas such as beehives to attempt to model our design after. Other than the morphological chart, forced analogy and crap shoot/brainstorming were how we got most of our concepts. For forced analogy we thought of various controllers to relate our project too, these things were tv remotes, gaming controllers, racing wheel simulators etc. We took bits and pieces from these preexisting ideas and applied them to our thought process to get more designs. Crapshoot/Brainstorming was how we got the rest of the ideas, and for this the group members listed anything that came to mind regardless of how good or bad the idea seemed.

Inside of our morphological chart we have assorted items listed that are viable solutions for each sub system function, to briefly discuss each this will show how we interpreted which of our designs were considered high low and medium fidelity by using various combinations of specifically high fi solutions etc.

Within our fit category with respect to the physical nature of buttons and operable controls we have thumbwheel adjustments, which is similar in respect to a mouse wheel operated with your thumb. This component is considered low-med fi as some are used in crafts, but not all crafts. Pushbuttons are the next solution, which are consider high fi in terms of the real crafts, they are included in every aircraft HOTAS and vary from craft to craft in terms of placement. Toggle switches are also considered a high fi solution as they represent many functions on multiple craft designs. Isotonic joysticks are the next solution, which are considered high fi with respect to the stick itself, however low fi with respect to buttons and switches, and finally a combination of all the above items, this was the most high-fidelity concept in this category because it represents a range of solutions on both known HOTAS, and inside of many different crafts.

For the form category, we have chosen to model this function based on the basic physical form of the entire unit and its ability for modularity. The first three solutions all represent the same traits, in high fidelity fashion with respect to the crafts themselves, however we are considering them med fi with respect to the solution of creating a design to fit multiple crafts. These three are resembling the F35, F16 and F22 HOTAS units onboard the craft. The next solution is the one we considered the highest fidelity with respect to our problem, the threaded grips for multiple crafts. The multiple grip covers for the single stick being considered high fi with respect to the solution however low fi with respect to having it be representative of multiple crafts.

The assembly category has three basic solutions that we determined. These are a separate throttle and stick, a combined throttle and stick, and a combined but modular for separability. The highest fidelity with respect to our solution became the combined but modular variant. With the combined throttle and stick being low fi, with the separate throttle and stick being considered medium fidelity

For the processing category, we have various solutions with respect to creating the internal components of the HOTAS with respect to what we believe can be accomplished in line with our subsystem problem. These four solutions are, the use of Arduino boards, python boards, raspberry pi, and custom PCB boards, we believe that the Arduino board will be the highest fidelity in this category due to our prior knowledge with those boards, however the other high fi solution would be creating a custom PCB, this just starts to creep outside of our scope. The python and the raspberry pi solutions are to be considered medium fi.

For communication, our choices became relevant with respect to communication between the throttle and stick, not to the main PC, this was narrowed down as our sponsor has set a requirement to have the unit connect to the PC via a USB-A type connection. Therefore, this leads to us using this as our highest fidelity solution, because it lowers cost of purchasing as well as fulfills the requirements of multiple problems. The others considered high fidelity are DV9, and ethernet(cat6), with the medium fi solutions being the USB-B(micro), and the USB C.

Under our sense category and within our brainstorming session we determined many solutions including using strain gages, pressure plates, GPS sensors, along with hall effect sensors, potentiometers, dc motors, and digital encoders. Some of the high fi solutions would be the strain gages, hall effect sensors, and digital encoders. Some of the medium fi solutions would include the potentiometer, the GPS sensor and the pressure plates, with the low fi being the DC motor.

The force category is representative of how we plan to implement feedback to the user and the physical means to do it. These would be the stepper motor, the DC motor, and the torsional spring. The high fi solution being the DC motor, the medium being the torsional spring, and the low fi being the stepper motor.

For our throttle displacement category, we based these off of benchmarks with existing designs and what is incorporated within the actual craft, these are sliding, rotating and slotted throttles. With the rotating being our high fi solution, sliding being the medium fi solution, and the slotted throttle being placed within the low fi category.

In the stick displacement section, we only thought of two unorthodox solutions to implementing the yaw of the stick, where pitch and roll will always be handled via the stick and some sensing means from above, however the yaw solutions were a twistable stick, or incorporating the yaw into the throttle. Some brainstormed ideas included having peddles such as in the real craft, but again that gets outside the scope of our problem. With this said the high fi solution became having the throttle with the yaw, as it is a more similar mechanism to the peddles used in real crafts, where the medium fi solution is the twistable stick.

For our power segment, we discussed the two possible solutions of power being either batteries or taking power from the PC itself from the communications connection. This led to the high fi solution being from the PC, with a battery being considered a low fi solution.

For mounting solutions, we considered a number of ways to accomplish this, however the most hi fi concept for our solution became the suction cups, and the mighty mug bottoms, with low fi being full chair mount, as this invalidates the ability to take the device home, with the clamp as another low fi solution. The medium fi solutions involve Velcro, and increased product weight

Finally, our materials category is all about the materials that will be used in the final prototype, we felt that the combination of materials would be the highest fidelity option, with plastics in that category as well for the solution to our particular problem, with fiber materials, polymers, and silicone being in the medium fidelity category, followed by metals in the low fi category. As we feel they would be the most time consuming and detrimental to the overall function.

Shown below is the morphological chart and how we used it to determine some of our more high fidelity concepts. The bulk and remainder of the concepts not shown here are shown in the appendix via more tables broken down into groups of 5 for ease.

Subsytems	Fit	Form	Assembly	Process	Communicatio	Sense	Force	Throttle Displacement	Stick Displacement	Power	Mounting	Material
Generated Concepts	Thumbwheel Adjustment	Resemble F35	Separate Throttle & Stick	Arduino	USB-A		Torsional Spring	Sliding Throttle	Twistable Stick	Battery	Suction Cups	Plastics
	Pushbutton	Resemble F16	Single Unit Throttle & Stick	Custom Circuit Board	USB-B 3.0	Hall effect sensers	Stepper Motor	Rotating Throttle	Yaw on Throttle not Stick	From Computer	Clamp	Metals
	Toggle Switches	Resemble F22	Combined, but Modular for Separation	Raspberry Pi	USB-C	Potentiometer	DC Motor	Slotted Throttle			Velcro	Combination
	Isotonic Joystick	Threaded Grips for multiple crafts		Python Board	DV9	Motor DC					Increased Base Weight	Silicone
	combination from above	multiple Grip Covers for single Stick			Ethernet	Encoder					Mighty Mug Bottoms	Polymers
											Full Chair Mount	Fiber Materials

Table 7: Morphological Chart

Concepts 1-10 derived from the morphological chart are shown in the following tables.

Concepts	1	2	3	4	5
Fit	combination of buttons/switches	Isotonic Joystick	combination of buttons/switches	combination of buttons/switches	combination of buttons/switches
Form	Threaded Grips for multiple crafts	Threaded Grips for multiple crafts	Resemble F35	multiple Grip Covers for single Stick	Threaded Grips for multiple crafts
Assembly	combined, but modular for separation	Separate Throttle & Stick	combined, but modular for separation	Separate Throttle & Stick	combined, but modular for separation
Process	Arduino	Arduino	Arduino	Arduino	Arduino
Communication	USB-A	Ethernet	USB-A	DV9	USB-A
Sense	Hall effect sensers	Hall effect sensers	Hall effect sensers	Potentiometer	Encoder
Force	DC Motor	DC Motor	DC Motor	Torsional Spring	DC Motor
Throttle Displacement	Rotating Throttle	Sliding Throttle	Rotating Throttle	Rotating Throttle	Slotted Throttle
Stick Displacement	Twistable Stick	Yaw on Throttle not Stick	Twistable Stick	Yaw on Throttle not Stick	Twistable Stick
Power	from Computer	From Computer	from Computer	From Computer	From Computer
Mounting	Mighty Mug Bottoms	Increased Base Weight	Full Chair Mount	Suction Cups	Mighty Mug Bottoms
Material	Combination	Plastics	Combination	Plastics	Combination

A brief example of how we used the morphological chart to determine some of our medium and high fidelity concepts is shown below. Each of the high fidelity concepts is described below the charts for greater clarity.

High Fidelity Concept 1

Concepts	6	7	8	9	10
Fit	combination of buttons/switches	combination of buttons/switches	combination of buttons/switches	combination of buttons/switches	combination of buttons/switches
Form	Resemble F35	multiple Grip Covers for single Stick	Threaded Grips for multiple crafts	Threaded Grips for multiple crafts	Resemble F35
Assembly	combined, but modular for separation	Separate Throttle & Stick	combined, but modular for separation	Separate Throttle & Stick	combined, but modular for separation
Process	Arduino	Arduino	Arduino	Arduino	Arduino
Communication	USB-A	USB-A	USB-A	USB-A	USB-A
Sense	Encoder	Potentiometer	Hall effect sensers	Potentiometer	Hall effect sensers
Force	DC Motor	Torsional Spring	DC Motor	DC Motor	Torsional Spring
Throttle Displacement	Rotating Throttle	Sliding Throttle	Rotating Throttle	Rotating Throttle	Rotating Throttle
Stick Displacement	Twistable Stick	Yaw on Throttle not Stick	Twistable Stick	Yaw on Throttle not Stick	Twistable Stick
Power	From Computer	From Computer	From Computer	From Computer	From Computer
Mounting	Mighty Mug Bottoms	Suction Cups	Clamp	Full Chair Mount	Clamp
Material	Combination	Plastics	Plastics	Combination	Combination

Subsytems	Fit	Form	Assembly	Process	Communication	Sense	Force	Throttle Displacement	Stick Displacement	Power	Mounting	Material
Generated Concepts	Thumbwheel Adjustment	Resemble F35	Separate Throttle & Stick	Arduino	USB-A		Torsional Spring	Sliding Throttle	Twistable Stick	Battery	Suction Cups	Plastics
	Pushbutton	Resemble F16	Single Unit Throttle & Stick	Custom Circuit Board	USB-B 3.0	Hall effect sensers	Stepper Motor	Rotating Throttle	Yaw on Throttle not Stick	From Computer	Clamp	Metals
	Toggle Switches	Resemble F22	Combined, but Modular for Separation	Raspberry Pi	USB-C	Potentiometer	DC Motor	Slotted Throttle			Velcro	Combination
	Isotonic Joystick	Threaded Grips for multiple crafts		Python Board	DV9	Motor DC					Increased Base Weight	Silicone
	combination from above	multiple Grip Covers for single Stick			Ethernet	Encoder					Mighty Mug Bottoms	Polymers
											Full Chair Mount	Fiber Materials

High Fidelity Concept 2

Subsytems	Fit	Form	Assembly	Process	Communication	Sense	Force	Throttle Displacement	Stick Displacement	Power	Mounting	Material
Generated Concepts	Thumbwheel Adjustment	Resemble F35	Separate Throttle & Stick	Arduino	USB-A		Torsional Spring	Sliding Throttle	Twistable Stick	Battery	Suction Cups	Plastics
	Pushbutton	Resemble F16	Single Unit Throttle & Stick	Custom Circuit Board	USB-B 3.0	Hall effect sensers	Stepper Motor	Rotating Throttle	Yaw on Throttle not Stick	From Computer	Clamp	Metals
	Toggle Switches	Resemble F22	Combined, but Modular for Separation	Raspberry Pi	USB-C	Potentiometer	DC Motor	Slotted Throttle			Velcro	Combination
	Isotonic Joystick	Threaded Grips for multiple crafts		Python Board	DV9	Motor DC					Increased Base Weight	Silicone
	combination from above	multiple Grip Covers for single Stick			Ethernet	Encoder					Mighty Mug Bottoms	Polymers
											Full Chair Mount	Fiber Materials

High Fidelity Concept 3

Subsytems	Fit	Form	Assembly	Process	Communication	Sense	Force	Throttle Displacement	Stick Displacement	Power	Mounting	Material
Generated Concepts	Thumbwheel Adjustment	Resemble F35	Separate Throttle & Stick	Arduino	USB-A		Torsional Spring	Sliding Throttle	Twistable Stick	Battery	Suction Cups	Plastics
	Pushbutton	Resemble F16	Single Unit Throttle & Stick	Custom Circuit Board	USB-B 3.0	Hall effect sensers	Stepper Motor	Rotating Throttle	Yaw on Throttle not Stick	From Computer	Clamp	Metals
	Toggle Switches	Resemble F22	Combined, but Modular for Separation	Raspberry Pi	USB-C	Potentiometer	DC Motor	Slotted Throttle			Velcro	Combination
	Isotonic Joystick	Threaded Grips for multiple crafts		Python Board	DV9	Motor DC					Increased Base Weight	Silicone
	combination from above	multiple Grip Covers for single Stick			Ethernet	Encoder					Mighty Mug Bottoms	Polymers
											Full Chair Mount	Fiber Materials

High Fidelity

1. The first high-fidelity concept uses a combination of thumbwheel adjustment, pushbuttons, toggle switches, and an isotonic Joystick. There will be a threaded section on the base of the stick to fit multiple grips. The stick and throttle base will be combined but modular to allow for separation if desired. The processor will be Arduino and it will communicate with the computer through USB-A. Hall effect sensors will be used to detect the aircraft orientation intent. The force feedback will be provided by a DC motor. The throttle actuation will only be rotation and the yaw of the aircraft will be controlled on the throttle. The power source will be from the computer and the bases will have suction cups on the bottom to hinder the HOTAS from sliding on the desk. We will use a combination of materials to make the HOTAS.

2. The second high-fidelity concept is similar to the first one in all categories of solutions. The only difference is that the throttle is manipulated with sliding motion instead of rotation.

3. The third high-fidelity concept is similar to the first one as well, the two solution differences are the sensor and the force feedback. A potentiometer would be used for the sensor and a torsional spring would be used for the feedback.

The following is a discussion of the concepts we determined to be medium fidelity. Most of these concepts were derived during our brainstorming and crap-shoot sessions. To have a completed concept and not just a single word or sentence most of these we have paired with solutions derived from the morphological chart to fully specify the intent of each given concept solution.

Medium Fidelity

1. Use a belt system to actuate the throttle. There would theoretically be no backlash in the system, this will be used with the concept 7 from the morphological chart, where the sliding throttle will be created with the belt system.
2. Base housing made of LEGO's, could be painted and glued together to form a rigid structure, this can be implemented with one of the concepts that uses plastics as a material.
3. Stick that doesn't move but interprets the amount of force being applied, this would be accomplished with either strain gages or pressure plates, along with a concept from the morphological chart such as concept 4 or concept 9 without the chair mount
4. Morph chart number 4
5. Use only COTS (Commercially off the Shelf) parts to make up the buttons and components

1.6 Concept Selection

The first step in creating our house of quality chart was to determine from our customer needs the requirements that the design must fulfill. These customer requirements are listed vertically on the left side of the chart. Following this, we transformed our targets into engineering characteristics to be able to compare our concepts too, later in this process. Once we had the engineering characteristics and customer requirements, we made a binary pairwise comparison matrix with our customer requirements to get our importance weight factor for the house of quality (shown below in blue).

Customer Requirement	1	2	3	4	5	Total
Easily Repairable	–	0	0	1	0	1
Under $4,000	1	–	0	1	1	3
Be able to integrate with Lockheeds software	1	1		1	1	4
Provide Feedback	0	0	0	–	0	0
Similar Functionality to Current Products	1	0	0	1	–	2
Total	3	1	0	4	2	

Table 18: Binary Comparison

This weight factor scales customer requirements, so the ones deemed more important will have a bigger impact on the engineering characteristics in the house of quality. Our highest importance weight factor ended up being “Able to Integrate with Lockheed's Software” and the least important was “Provide Feedback”. Feedback ended up with a weight factor of 0 but we used a weight factor of 1 for the house of quality so that it would have some effect on our outcome. For example, in calculating our raw score, our importance weight factor for the customer requirement “under $4,000” was 3, and under our cost column corresponding to that customer requirement we have a 9, so we multiply the 3 times 9 to get a total of 27, this value is added into our raw score for cost. The value of 9 came directly from our group saying that cost significantly effects meeting the requirement of being under $4,000, this value could have also been 0 for having no correlation, 1 for having slight correlation or 3 for having moderate correlation.

		Engineering Characteristics									
Improvement Direction		↑	↓	↓	↓	↑	↑	-	-	↑	↑
Units		Years	$	n/a	ms	MHz	Mpa	lbs	n/a	lbsf	n/a
Customer requirements	Importance Weight Factor	Lifespan	Cost	Design Complexity	Latency/Transfer Speed	Frequency	Material Strength	Weight	Shape	Force	Repairability
Easily Repairable	1	1	3	3	1	0	3	0	9	0	9
Under $4,000	3	0	9	9	3	3	3	3	1	3	3
Be able to Integrate With Lockheeds Software	4	0	1	1	3	3	0	0	0	0	0
Provide Feedback	1	0	3	1	3	1	3	1	1	9	1
Similar Functionality to Current Products	2	3	9	3	3	3	0	3	3	0	0
Raw Score	249	7	55	41	31	28	15	16	19	18	19
Relative Weight %		2.81	22.09	16.47	12.45	11.24	6.02	6.43	7.63	7.23	7.63
Rank Order		9	1	2	3	4	7	6	5	8	5

Table 19: House of Quality

After repeating this process throughout the entire table, it was found that our top three highest raw scores were Cost, Design Complexity and Latency/Transfer Speed. The relative importance percentage for each was 22.09%, 16.47% and 12.45% respectively. This tells us that when selecting our final concept, it is more important for our design to satisfy these three engineering characteristics more so than saying satisfy five of the less important ones, but not satisfying the top three.

The Pugh charts were the next phase in our concept selection. These tables compare concepts to each other, rather than our customer requirements to engineering characteristics like the house of quality. The way this table works is by first selecting a datum, this datum being a preexisting design or a one of our concepts, and this datum is the basis for comparing the other concepts too. Then for each concept you compare it to the datum for each engineering characteristic and determine if the concept is satisfactory (S) to the datum, is better than the datum (+) or worse than the datum (-). Once this is done for all the concepts the number of plusses and minuses is totaled, and from there you can choose to eliminate concepts with few pluses and lots of minuses and select the next datum from the highest number of pluses and fewest number of minuses to use in the next iteration of the Pugh charts. With the new datum selected the process is repeated until the number of concepts has been narrowed down.

Our first Pugh chart compared our 5 medium fidelity and our 3 high fidelity concepts to the Wraith Systems HOTAS as the initial benchmark to get the first datum for the next Pugh chart. Concepts 1-3 are the high-fidelity concepts listed in the prior concept generation, and concepts 4-8 are the five medium fidelity concepts listed in the concept generation section as well. In looking at the results from this chart, the three high fidelity concepts, 1-3, all had three plusses and six minuses. It is to be expected that the Wraith HOTAS will outperform in almost all categories besides lifespan, cost and repairability because these are the three engineering characteristics that we are going to be attempting to improve upon. Since there was no clear winner, we decided to set concept 1 as our datum for the next Pugh chart since concept 1 is a high-fidelity concept and was tied for the greatest number of pluses and least number of minuses.

		Concepts							
Engineering Chars	Wraith Systems	1	2	3	4	5	6	7	8
Lifespan	Datum	+	+	+	+	+	+	+	+
Cost		+	+	+	+	+	+	+	+
Latency/Transfer Speed		-	-	-	-	-	-	-	-
Frequency		-	-	-	-	-	-	-	-
Material Strength		-	-	-	-	-	-	-	-
Weight		-	-	-	-	-	-	-	-
Shape		-	-	-	-	-	-	-	-
Force		-	-	-	-	-	-	-	-
Repairability		+	+	+	+	+	+	+	+
Pluses		3	3	3	3	3	3	3	3
Minuses		6	6	6	6	6	6	6	6

Table 20: Pugh Chart I

The next Pugh chart had concept 1 as the datum, and after comparing all the concepts it was found that concept three had the greatest number of pluses with a reasonable number of minuses, so this was chosen as our next datum. Concept 6 and 7 only had one plus and a lot of minuses so these concepts were removed from the next Pugh chart.

		Concepts						
Engineering Chars	Concept 1	2	3	4	5	6	7	8
Lifespan	Datum	S	-	S	-	S	S	S
Cost		-	+	-	+	-	+	+
Latency/Transfer Speed		S	-	S	S	S	-	S
Frequency		S	S	S	S	S	S	S
Material Strength		S	S	S	-	S	-	S
Weight		S	S	+	-	S	-	S
Shape		S	+	-	S	S	S	-
Force		S	S	S	-	+	-	S
Repairability		S	+	-	+	-	S	+
Pluses		0	4	1	2	1	1	2
Minuses		1	2	3	4	2	4	1

Table 21: Pugh Chart II

The third Pugh chart had concept 3 as the datum. The concepts 1, 2, 5 and 8 all had two pluses where concept 4 had just one plus but less minuses than concept 5 and due to this we decided to remove concept 5 from the next Pugh chart.

	Concepts					
Engineering Chars	Concept 3	1	2	4	5	8
Lifespan	Datum	+	S	S	-	S
Cost		-	+	-	+	+
Latency/Transfer Speed		+	+	S	S	S
Frequency		S	S	S	S	S
Material Strength		S	S	S	-	S
Weight		S	S	+	-	S
Shape		-	S	-	S	-
Force		-	-	S	-	S
Repairability		-	-	-	+	+
Pluses		2	2	1	2	2
Minuses		4	1	3	4	1

Table 22: Pugh Chart III

For the final Pugh chart, concept 2 was chosen as the datum. Concepts 1 and 4 both had one plus, but concept 4 had three minuses whereas concept 1 did not have any minuses. From this chart it was shown that concept 3 would be the next datum, and potentially the overall winner in this selection stage.

	Concepts				
Engineering Chars	Concept 2	1	3	4	8
Lifespan	Datum	S	-	S	S
Cost		S	+	-	+
Latency/Transfer Speed		S	S	S	S
Frequency		S	-	S	S
Material Strength		S	S	S	S
Weight		S	S	+	S
Shape		+	+	-	-
Force		S	S	S	S
Repairability		S	+	-	+
Pluses		1	3	1	2
Minuses		0	2	3	1

Table 23: Pugh Chart IV

After analyzing all four Pugh charts it was found that concepts 1, 2, 3 and 4 were selected to advance to the AHP portion of the concept selection for further determination. The reasoning behind this is that concepts 1, 2 and 3 always performed better than concepts 4-8 even though at times concept 2 might've outperformed concept 3 or vice versa. The reason behind selecting concept 4 was that even though it might not have outperformed concepts 1-3, it still did better many of the others and it can only be beneficial to include a concept that is on the cusp of being selected because it may shock us in the AHP section, or it can just further solidify that one of the other three concepts are the correct choice.

The next process we used was analytical hierarchy, this would allow us to further refine and determine which of our concepts would be the overall winner and selected to move into the next phase of our project. The first step of this process shown below involved using our engineering characteristics and comparing them to each other to determine which were the most important for our final decisions. This table ultimately let us know that the cost characteristic was the most important by far, followed by repairability and transfer speed/latency. These characteristics are used in further comparisons below, and their weights respectively are 30%, 19.3%, and 16.7%, these are shown highlighted in the third table below as well. The first table below shows the comparison, where the second is the normalized data from the comparison matrix. The third table shown is part of the normalized comparison but it's split for viewing purposes. It shows our consistency in not introducing bias into the choices that we made, and that the decisions we made line up across the whole chart, this is numerically shown in each of the normalized comparisons by the consistency ratio being less than 0.10.

AHP information tables

Engineering Characteristics AHP	Lifespan	Cost	Transfer Speed/Latency	Frequency	Material Rigidity	Weight	Shape	Force	Repairability
Lifespan	1	1/7	1/3	1/3	3	3	7	3	1/3
Cost	7	1	3	3	7	9	7	9	3
Transfer Speed/Latency	3	1/3	1	1/3	5	7	5	7	3
Frequency	3	1/3	3	1	5	5	5	7	1/5
Material Rigidity	1/3	1/7	1/5	1/5	1	1	3	1	1/7
Weight	1/3	1/9	1/7	1/5	1	1	1	1	1/7
Shape	1/7	1/7	1/5	1/5	1/3	1	1	1	1/5
Force	1/3	1/9	1/7	1/7	1	1	1	1	1/9
Repairability	3	1/3	1/3	5	7	7	5	9	1
Total	18.14	2.65	8.35	10.41	30.33	35.00	35.00	39.00	8.13

Table 24: Engineering Characteristics AHP comparison

Engineering Characteristics N AHP	Lifespan	Cost	Transfer Speed/Latency	Frequency	Material Rigidity	Weight	Shape	Force	Repairability
Lifespan	0.055	0.054	0.040	0.032	0.099	0.086	0.200	0.077	0.041
Cost	0.386	0.377	0.359	0.288	0.231	0.257	0.200	0.231	0.369
Transfer Speed/Latency	0.165	0.126	0.120	0.032	0.165	0.200	0.143	0.179	0.369
Frequency	0.165	0.126	0.359	0.096	0.165	0.143	0.143	0.179	0.025
Material Rigidity	0.018	0.054	0.024	0.019	0.033	0.029	0.086	0.026	0.018
Weight	0.018	0.042	0.017	0.019	0.033	0.029	0.029	0.026	0.018
Shape	0.008	0.054	0.024	0.019	0.011	0.029	0.029	0.026	0.025
Force	0.018	0.042	0.017	0.014	0.033	0.029	0.029	0.026	0.014
Repairability	0.165	0.126	0.040	0.480	0.231	0.200	0.143	0.231	0.123
Total	1	1	1	1	1	1	1	1	1

Table 25.1: Engineering Characteristics normalized comparison part 1

Weighted total	Weighted sum	Conistency vector	average consistency	10.0820
0.076	0.716	9.433	n value	9
0.300	3.240	10.806	Consistency index	0.1353
0.167	1.770	10.628	Ri (lookup value (n))	1.45
0.156	1.615	10.375	Consistency Ratio	0.0933
0.034	0.319	9.376		
0.026	0.250	9.786		
0.025	0.243	9.792		
0.025	0.235	9.589		
0.193	2.116	10.953		

Table 25.2: Engineering Characteristics normalized comparison part 2

The next step in our AHP was to create a few more comparisons using the concepts that had been selected using the Pugh charts in the previous process. This involved taking our highest ranked engineering characteristics and thinking in terms of each, while comparing each of our four concepts against each other in these matrices using those characteristics. From the first set of tables below, we used cost as the main means of comparison, this led to a clear winner in this category with a clear split between the others. The winner of this category being concept 3 with a weighted total of 62.3%, with the next being concept 4 evaluated to be 21.6%. Our data shown below also indicates that we were consistent with our selections. With the consistency ratio again being below 0.10.

Cost AHP tables

Cost AHP	Concept 1	Concept 2	Concept 3	Concept 4
Concept 1	1	1/3	1/7	1/5
Concept 2	3	1	1/7	1/3
Concept 3	7	7	1	5
Concept 4	5	3	1/5	1
Total	16.00	11.33	1.49	6.53

Table 26: Cost AHP comparison

Cost N AHP	Concept 1	Concept 2	Concept 3	Concept 4
Concept 1	0.063	0.029	0.096	0.031
Concept 2	0.188	0.088	0.096	0.051
Concept 3	0.438	0.618	0.673	0.765
Concept 4	0.313	0.265	0.135	0.153
Total	1	1	1	1

Table 27.1: Cost normalized comparison part 1

weighted total	weighted sum total	consistency vector	average consistency	4.2457
0.055	0.222	4.065	n value lookup	4
0.106	0.431	4.075	Consistency Index	0.0819
0.623	2.827	4.535	Random index value	0.89
0.216	0.931	4.308	Consistency Ratio	0.0920
1				

Table 27.2: Cost normalized comparison part 2

The next step in the AHP was using our second ranked characteristic of repairability. This comparison was similar to the one above, where now we are using repairability as the deciding factor and comparing between each concept again, this variant of the tables shows that again our concept 3 is the clear winner this time as well, with concept 4 being the next best. With each concept having 67.6%, and 16.7% respectively. Our consistency ratio shows that we are consistent in our choices for this matrix as well.

Repairability AHP charts

Repairability AHP	Concept 1	Concept 2	Concept 3	Concept 4
Concept 1	1	3 1/33	1/7	1/3
Concept 2	1/3	1	1/9	1/3
Concept 3	7	9	1	7 3/71
Concept 4	3	3	1/7	1
Total	11.33	16.03	1.40	8.71

Table 28: Repairability AHP comparison

Repairability N AHP	Concept 1	Concept 2	Concept 3	Concept 4
Concept 1	0.088	0.189	0.102	0.038
Concept 2	0.029	0.062	0.080	0.038
Concept 3	0.618	0.561	0.716	0.809
Concept 4	0.265	0.187	0.102	0.115
Total	1	1	1	1

Table 29.1: Repairability normalized comparison part 1

weighted total	weighted sum total	consistency vector	average consistency	4.2607
0.104	0.415	3.976	n value lookup	4
0.052	0.218	4.158	Consistency Index	0.0869
0.676	3.055	4.519	Random index value	0.89
0.167	0.734	4.390	Consistency Ratio	0.0976
1				

Table 29.2: Repairability normalized comparison part 2

Our final comparison below is a chart of frequency and resolution while comparing against each of the concepts again. This comparison is different as we are looking at this in respect with cost and overall functionality, this shows that some of our concepts are more high fidelity, however we need something that is lower than that. But not the least, the highlighted concept below was weighted the lowest fidelity and functionality, this was concept 4, with the value of 4.7%. with the second lowest being concept 3 with 12.7%. Again, showing consistency in choices below as well.

Frequency and resolution AHP charts

Frequency(resolution) AHP	Concept 1	Concept 2	Concept 3	Concept 4
Concept 1	1	1	5	7 3/71
Concept 2	1	1	5	7 3/71
Concept 3	1/5	1/5	1	5
Concept 4	1/7	1/7	1/5	1
Total	2.34	2.34	11.20	20.08

Table 30: Frequency and resolution AHP comparison

Frequency(resolution) N AHP	Concept 1	Concept 2	Concept 3	Concept 4
Concept 1	0.427	0.427	0.446	0.351
Concept 2	0.427	0.427	0.446	0.351
Concept 3	0.085	0.085	0.089	0.249
Concept 4	0.061	0.061	0.018	0.050
Total	1	1	1	1

Table 31.1: Frequency and resolution normalized comparison part 1

weighted total	weighted sum total	consistency vector	average consistency	4.2172
0.413	1.794	4.347	n value lookup	4
0.413	1.794	4.347	Consistency Index	0.0724
0.127	0.528	4.153	Random index value	0.89
0.047	0.190	4.021	Consistency Ratio	0.0813
1				

Table 31.2: Frequency and resolution normalized comparison part 2

Finally, after much deliberation and charts, we decided that our chosen concept based on an overwhelming victory in multiple steps of the process is concept 3, with lower costs, manageable repairability, and decent overall frequency and resolution functionality in comparison to some of the other concepts that were used and compared against. This concept is shown below via the morphological chart method used to create it. Soon we will begin modeling and prototyping various components of this design to find if our outcomes have proven to be the best decision.

High Fidelity Concept 3 (final selection)

Subsytems	Fit	Form	Assembly	Process	Communication	Sense	Force	Throttle Displacement	Stick Displacement	Power	Mounting	Material
Generated Concepts	Thumbwheel Adjustment	Resemble F35	Separate Throttle & Stick	Arduino	USB-A		Torsional Spring	Sliding Throttle	Twistable Stick	Battery	Suction Cups	Plastics
	Pushbutton	Resemble F16	Single Unit Throttle & Stick	Custom Circuit Board	USB-B 3.0	Hall effect sensers	Stepper Motor	Rotating Throttle	Yaw on Throttle not Stick	From Computer	Clamp	Metals
	Toggle Switches	Resemble F22	Combined, but Modular for Separation	Raspberry Pi	USB-C	Potentiometer	DC Motor	Slotted Throttle			Velcro	Combination
	Isotonic Joystick	Threaded Grips for multiple crafts		Python Board	DV9	Motor DC					Increased Base Weight	Silicone
	combination from above	multiple Grip Covers for single Stick			Ethernet	Encoder					Mighty Mug Bottoms	Polymers
											Full Chair Mount	Fiber Materials

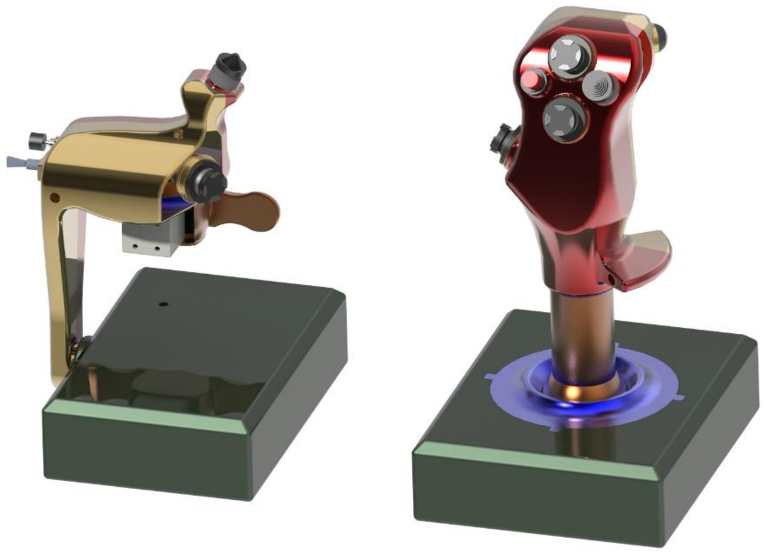
Chapter Two: EML 4552C

2.1 Restated Project Definition and Scope

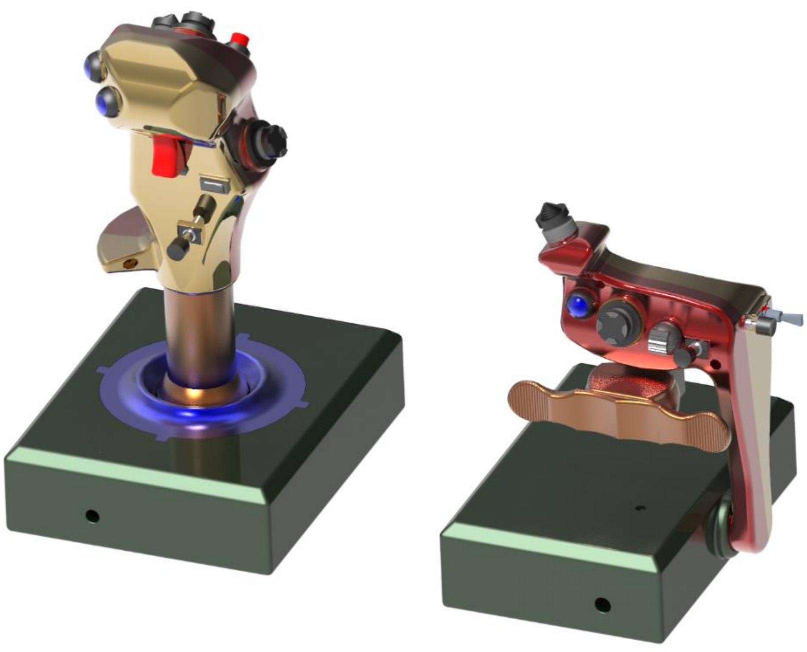
The objective of this project is to create a low-cost Hand-On Throttle and Stick (HOTAS) system to support the Pilot Training Devices (PTD) product line. The product will replicate the throttle control assembly and control stick of various fighter aircrafts.

2.2 Results & Discussion

The final assembly met most of the targets that were set at the beginning of the project. The modularity aspect of this project was successfully implemented into the stick. All of its buttons were connected to the printed circuit board with modular connectors. This allows the user replace buttons without having to solder any connections if the replacement button already has the connector attached to it. Also, the stick connects to its base with a mini din connector. This modular connection is what allows the HOTAS system to implement multiple grips. The throttle was too small to fit all of the modular connectors for the buttons in, so its buttons were directly wired to the printed circuit board. The din connector between the throttle and its base was successfully implemented. This also allows for different throttle units to connect to the base as long as it has the same din connector wiring. Finally the entire HOTAS system was determined to cost $1570.02 to completely build and assemble, well under our allotted budget of $2000.00 making that goal and parameter a success. Shown below is a graphical breakdown of how funding was allocated throughout our project.



Final Assembly Front view



Final assembly rear view

Fits 95% of Aviators

In order to achieve this function, the dimensions of the final stick and throttle must coincide with the mil standard. These have been shown to be valid in most of the cases discussed inside of Mil. Std. 1472, including aviators hand and finger sizes, strengths of motion, torque application, and button resistance ranges. Some of these may be close to or out of our targets, however without changing or compromising on our commercial off the shelf products these goals could not all be met, this is likely one of the most difficult targets for us to achieve as it requires allot of testing, and user validation with a significant amount of end users, which is currently not possible, therefore this target has only been 75% achieved.

Integrating with Lockheed Martin Software

This function was validated by ensuring that the HOTAS is able to control the F-35 aircraft in the Prepar3D software. This was done by implementing two micro controllers attached to the computer system, one in each base, each with a separate function of either throttle or stick. We tested the communication with Prepar3d in multiple stages and determined that the goal of integrating with the simulator software was a 100% success allowing full use of all buttons switches and sensors when implementing both digital and analog devices, the only thing required of the user is to map the required functions to a specific electronic output.

Implement with Various Craft Design

The HOTAS must be able to accommodate at least 55 separate signals in order for this function to be validated. There was a total of 44 signals that were successfully processed after electronic and mechanical integration. Although all of the signals were successfully processed when tested before the final integration when the mechanical and electronic components were separate, however the printed circuit board in the throttle was not integrated correctly and electrical failure occurred. This caused all of the digital signals in the throttle to not function properly. That being said, the printed circuit boards in the stick processed the digital data well. The overall electrical infrastructure does allow for the project to meet the target of 55 inputs, and surpasses that to 64 inputs total with 8 shift registers being implemented. But due to the assembly, the final target was not met. Therefore this target was met with 75\% success due to success before integration and 1/2 system failure post integration.

Filter and Process I/O

This function will be verified when the buttons trigger the appropriate signals in Prepar3D. This function was validated because the mapped buttons on the stick triggered their appropriate responses. The figure shows the mapping of the Ailerons and elevators to the outputs from the stick potentiometers. All of the analog outputs from the HOTAS were successfully apped in Prepar3D. The digital buttons on the stick were mapped in a similar manner.

Detect Aircraft Control Intent

This metric and target were set to be 20 milliseconds, this particular metric was in response to the analog sensors (potentiometers). These sensors are used to control the main modes of directional travel including pitch, roll, yaw, and throttle response. These sensors have a response time 35 of milliseconds not achieving the target of under 20 millisecond response. Notably when piloting an aircraft inside of Prepar3d latency is not noticed and is not a huge consideration, given we are novice pilots, with one of us having a pilot's license.

Detect Signal Activation

This function above will be verified when the measured latency from the digital buttons to the software is less than 20 milliseconds. This is in reference to the arrays of buttons incoming from the printed circuit boards through the din pin connection into the Arduino boards. With the throttle and stick printed circuit board designs varying the latency of each also is different, with the latency of the stick with 5 shift registers being 35 milliseconds, and the latency from the throttle with 3 shift registers being 25 milliseconds. This shows that we have not met our target for this metric.

Output Signals

The transfer speed of the HOTAS unit was limited by the transfer speed of the microcontroller that it used. The ATmega32u4 microchip can transfer data up to 12 megabits per second . There is no other software required for this chip to be recognized as a USB device .So, the transfer speed from the micro USB cable is what is used for the metric used to validate this function. The transfer speed of the USB micro-B cable is 480 megabits per second, which is less than the target set at the beginning of the project.

Operate Throttle and Stick Buttons

This function will be validated when the final stick travels a total of 70 degrees in both the x and y directions. Also when the throttle rotates a total of 65 degrees. This is a 100% success as follows. The mechanical designs implemented allow exactly the range specified for the travel and rotation of each unit, with mechanical stops being used to limit the ranges of each. A joystick potentiometer is used inside of the stick to control the pitch and roll, this same sensor is used to control the yaw on the throttle unit with a 40 degree range of motion. The throttle uses a rotary precision potentiometer attached to a simple gear train to allow for greater accuracy during the 0-65 degree rotation.

2.3 Conclusions

Overall, this project was successful regardless of not meeting every target. At the conclusion of this project, a low-cost HOTAS was designed, built and functional within Prepar3D. A fighter aircraft stick and throttle were 3D printed featuring various buttons mounted to the units that resembled current fighter aircraft. These buttons functioned using a combination of custom printed circuit boards and an Arduino Leonardo micro-controller to process and turn the button actuation and HOTAS movements into outputs in the flight simulator software. The stick and throttle also feature modularity, allowing various sticks and throttles to be implemented with the bases via a mechanical and electrical connection. Due to complications with the assembly of the throttle, the digital buttons did not function, but the throttle was still able to be used to control the aircraft's speed. Additionally, complications with 3D printing did not allow the throttle to be completely modular as intended, but the concept of modularity was proven to be successful mechanically and electrically before final integration. With modularity being a huge success within the stick unit, and the throttle being semi-successful, the HOTAS was able to be used to fly and operate a F-35 Lightining II in a manner comparable to pre-existing HOTAS' yielding a successful project overall. The overall cost was less than $2,000. The trade-off for making the unit cost effective is the latency of the unit as well as the material used to manufacture it.

2.4 Future Work

Some improvements to this design include the following: implement HOTAS with other throttle and stick units, resizing the throttle to fit all of the button connectors, redesign the printed circuit board, and implementing a Teenzy instead of the arduino Leonardo. In order to demonstrate the modularity of HOTAS, designing different throttle and stick grips with other buttons could be benificial. All of the analog input pins could be connected inside of the base even though there wouldn't have to be a connection through the mini-din connector. This way, the stick and throttle grips wouldn't have to have the same number of analog signals.

The throttle was shaped to fit comfortably in most aviators hands. However, the size of the button connectors were not taken into account when the throttle was designed. This could be better implemented in future attempts at this project. Also, the size of the connectors themselves could be sourced better so that they could fit into the throttle. The printed circuit boards work well but could be redesigned to be more robust. They could be designed to have connectors directly mounted onto them. There was a mistake when designing the boards that accommodated more than two shift registers. The mistake was fixed by soldering a wire where there should have been a trace. This flaw was fixed in the program, but was never reprinted due to cost. Another issue with the printed circuit boards was the layout. It wasn't designed very well in that there was no clear standard for how the connections were to be made. Although the size of the board was not a problem in this design, it could be for other designs. A smaller printed circuit board could be used if the surface mount components were assembled with machinery instead of by hand.

The latency was was a major drawback for the success of this project. The processing speed of the micro-controller is a hard upper bound. A faster micro-controller, such as the Teenzy, could be used instead of the Arduino Leonardo in order to improve the speed of the

HOTAS. This way, there would be less of a trade-off for cost-effectiveness and the latency of the HOTAS unit. Some HOTAS models on the market have force feedback to resist the user and increase the fidelity of the unit. In order to make this project more realistic for the user, there could be a feedback profile that the user selects from depending on the vehicle that they intend to control. These changes would make the assembly more straightforward, decrease the latency of the project, and provide a more realistic experience for the end user.

Appendices

Appendix A: Code of Conduct

Project statement

Lockheed-Martin - Low-Cost HOTAS Design for Pilot Training Devices

Lockheed Martin needs a low-cost Hands-On Throttle and Stick (HOTAS) system to support the Pilot Training Devices (PTD) product line. The product will replicate the throttle control assembly and control stick of fighter aircraft. It is desired to have one common design that supports multiple aircraft through an interchangeable outer grip for the control stick that is specific to each aircraft. This project will include the electrical and mechanical aspects of the HOTAS devices. The device must output the appropriate signals in response to stick and throttle position and pressing of buttons. The stick control shall provide progressive resistance in proportion to the speed and angle of maneuver of the aircraft.

Mission statement

To apply knowledge learned throughout our coursework to engineer a sound solution for our client within given parameters.

Team roles

Patrick Dixon - Design and Mechatronics Engineer:

The design engineer will help coordinate overall design throughout the project and overall geometry creation through computer aided drafting and design. The mechatronics engineer will coordinate the bridge between electrical and mechanical systems, with an emphasis on sensors and actuators.

Robert Craig - Control Systems Engineer:

The controls engineer is responsible for designing the controls for the dynamics of the project. This includes implementing the code required and tuning the gains for the controller among other tasks related to linear control systems.

Robert Blount - System Engineer:

The System Engineer supports programs throughout the entire program life cycle and are the glue that helps programs ensure they meet all customer and mission requirements

Connor Chuppe - Test Engineer:

The test engineer is responsible for creating a process that would best test the product to ensure it meets the specified targets and functions properly. Test engineers can also be responsible for creating a way the test can be carried out in order to make sure all aspects of the product were covered in the testing.

Extra Duty Assignments and Tasks

Volunteers first, then assigned based on group discussion, each task will be evaluated and typically assigned to the individual most willing/able to perform the task otherwise.

Communication

All communication between team 512 will be done through phone calls, text messages, school email, canvas, basecamp, and zoom meetings. All notifications, email, and text messages sent out between team members will be responded to within a 24-hour time frame. Scheduling will be done through Basecamp software; this will include meetings and personal scheduling conflicts to appropriately manage time.

Dress code

For meetings within the group via zoom, any casual attire is allowed but pajamas or offensive clothing, etc. is not allowed. Meeting with the sponsor or faculty advisor semi-formal attire such as a polo and pants can be worn (business casual). For professional in person meetings and presentations, navy blue suits will be worn with appropriate shoes and belts. Hair styles are up to each individual group member as long as you are neatly groomed. May further match colors at a later date with shirts and ties.

Attendance policy

Unless a valid reason is given, all scheduled team meetings will be mandatory, with attendance being kept only in the event of an absence. Should a member not attend or provide an invalid reason for not attending, then they will first be addressed within the group. If the behavior persists (third time), then it will be reflected in the peer evaluations and superiors may be notified for further disciplinary action.

Valid reasons for missing a scheduled meeting includes medical emergencies, travel emergencies, and school emergencies. Any other scenarios will be handled on a case by case basis on the condition that 48-hour notice will be given prior to the start of the scheduled meeting. Nonvalid reasons for missing a scheduled meeting include forgetting the meeting. What is a valid reason for missing a meeting?

Statement of understanding:

Each student member of team 512 for the Lockheed Martin Sr. Design project has read, acknowledged, and submitted information contained in this document. Each understands their personal roles and responsibilities to the group.

Signed:

Robert Blount

Connor Chuppe

Robert Craig

Patrick Dixon

Appendix B Figures and Tables

A series of questions were asked to our sponsor in order to get a better understanding of what he was looking for in our project. The statements he gave in response to our questions were then interpreted into need statements that will be translated into targets and metrics later on.

Table 1

This is a list of questions asked to our sponsor Andrew Filiault and his responses. The interpreted needs are on the right

Questions	**Customer Statements**	**Interpreted need**
How many units are expected to be produced?	If all goes well, ~1,000 units and possibly more.	Design needs to be easily reparable.
How will the unit be implemented into your system?	It'll be mounted on a desktop and used in software training for a variety of military vehicles	Design needs to fit variety of military vehicle handles.
What is considered Low Cost?	Current models are around $8,000	Final Design needs to be under $4,000
Are we taking an existing design to modify or completely making a new design?	Building from the ground up	Create an original design
Are we making our own grips or using grips from existing aircraft?	Creating your own grip	Grip can be any design as long as its functional
Should we make a base, or will it be connected to an existing simulator?	You will need to make a base	HOTAS will be used on a desktop simulator
How many buttons and switches etc., what kind of functionality and accuracy is intended?	Reference current models. Design will be used for low fidelity training.	HOTAS needs to have the same functionality as most current models
What kind of software will be used?	Prepar3d is software used.	Needs to be able to integrate with software.
What are the expectations for the feedback?	Device should provide resistance dependent on relative speed.	HOTAS needs to provide resistance proportional to the simulated speed of the military vehicle

Table 2

This is a Basic Functional Decomposition Calculation Table. It allows for us to see which minor functions have the most overlap with major functions

System	Major System	Minor System	Fuction	Fit	Form	Assembly	Process	Communicate	Sense	Force	Displace	Provide Feedback	Row Total
HOTAS	Ergonomics	Fit	Conform to MIL standard 1472	1	1	0	0	0	0	1	0	0	3
			Integrate with Current Lockheed System	1	1	1	0	1	1	0	0	0	5
		Form	Support Multiple Modular Grips	1	1	1	0	0	0	1	0	0	4
			Implement Various Craft Designs	0	1	0	0	0	0	1	1	1	4
				0	0	0	0	0	0	0	0	0	0
		Assembly	Integrate with components	0	1	1	0	0	0	0	0	0	2
	Electronics	Process	Filter and Process I/O Data	0	0	0	1	1	1	0	0	1	4
		Communication	Input Feedback Signals	0	0	1	1	1	1	0	0	0	4
			Output Signals	0	1	1	0	1	0	0	0	0	3
		Sense	Detect Aircraft Control Intent	0	0	0	0	0	1	0	1	0	2
			Detect Signal Activation	0	0	1	0	0	1	0	1	0	3
	Mechanical	Force	Provide Feedback	0	1	1	0	0	0	1	1	1	5
		Displacement	Operate Throttle, Stick, and Buttons	0	1	1	0	1	1	1	1	1	7

Table 3

Pairwise Comparison Matrix Evaluation of Minor Functions. Evaluates the importance of each minor function with respect to one another

Function	Conform to MIL standard 1472	Integrate with Current Lockheed System	Support Multiple Modular Grips	Implement Various Craft Designs	Integrate with components	Filter and Process I/O Data	Input Feedback Signals	Output Signals	Detect Aircraft Control Intent	Detect Signal Activation	Provide Feedback	Operate Throttle, Stick, and Buttons
Conform to MIL standard 1472	1	5	3	7	1	0.11	0.14	0.14	0.11	0.14	9	0.33
Integrate with Current Lockheed System	0.20	1	3	5	1	0.20	0.33	0.33	0.11	0.33	5	0.20
Support Multiple Modular Grips	0.33	0.33	1	1	0.33	0.14	0.14	0.14	0.11	0.14	3	0.14
Implement Various Craft Designs	0.14	0.20	1	1	0.20	0.14	0.14	0.14	0.14	0.14	0.33	0.11
Integrate with components	1	1	3	5	1	0.20	0.33	0.33	0.11	0.20	0.20	0.20
Filter and Process I/O Data	9	5	7	7	5	1	7	7	1	1	5	1
Input Feedback Signals	7	3	7	7	3	0.14	1	1	0.20	0.20	3.00	0.20
Output Signals	7	3	7	7	3	0.14	1	1	0.20	0.20	3.00	0.20
Detect Aircraft Control Intent	9	9	9	7	9	1	5	5	1	5	7	1
Detect Signal Activation	7	3	7	7	5	1	5	5	0.200	1	0.14	3
Provide Feedback	0.11	0.20	0.33	3	5	0.20	0.33	0.33	0.14	7	1	0.33
Operate Throttle, Stick, and Buttons	3	5	7	9	5	1	5	5	1	0.33	3	1
Sum Total	44.787	35.733	55.333	66.000	38.533	5.283	25.429	25.429	4.330	15.695	39.676	7.724

Table 4

Normalized Comparison Matrix gives an idea of the most important functions

Function	Conform to MIL standard 1472	Integrate with Current Lockheed System	Support Multiple Modular Grips	Implement Various Craft Designs	Integrate with components	Filter and Process I/O Data	Input Feedback Signals	Output Signals	Detect Aircraft Control Intent	Detect Signal Activation	Provide Feedback	Operate Throttle, Stick, and Buttons	Weighted Totals	Weighted Totals Percentile	Consistency Vector	Average Consistency	N Value	Random index Value for n = 12
Conform to MIL standard 1472	0.0223	0.1399	0.0542	0.1061	0.0260	0.0210	0.0056	0.0056	0.0257	0.0091	0.2268	0.0432	0.0571	5.71	0.7231	0.9864	12	1.54
Integrate with Current Lockheed System	0.0045	0.0280	0.0542	0.0758	0.0260	0.0379	0.0131	0.0131	0.0257	0.0212	0.1260	0.0259	0.0376	3.76	0.8545			
Support Multiple Modular Grips	0.0074	0.0093	0.0181	0.0152	0.0087	0.0270	0.0056	0.0056	0.0257	0.0091	0.0756	0.0185	0.0188	1.88	1.1042			
Implement Various Craft Designs	0.0032	0.0056	0.0181	0.0152	0.0052	0.0270	0.0056	0.0056	0.0330	0.0091	0.0084	0.0144	0.0125	1.25	1.3337	Consistency Index	Consistency Ratio	these values are < 0.10 making
Integrate with components	0.0223	0.0280	0.0542	0.0758	0.0260	0.0379	0.0131	0.0131	0.0257	0.0127	0.0050	0.0259	0.0283	2.83	0.8440	-1.0012	-0.6502	the comparisson consistent
Filter and Process I/O Data	0.2009	0.1399	0.1265	0.1061	0.1298	0.1893	0.2753	0.2753	0.2309	0.0637	0.1260	0.1295	0.1661	16.61	1.0485			
Input Feedback Signals	0.1563	0.0840	0.1265	0.1061	0.0779	0.0270	0.0393	0.0393	0.0462	0.0127	0.0756	0.0259	0.0681	6.81	0.6968			
Output Signals	0.1563	0.0840	0.1265	0.1061	0.0779	0.0270	0.0393	0.0393	0.0462	0.0127	0.0756	0.0259	0.0681	6.81	0.6968			
Detect Aircraft Control Intent	0.2009	0.2519	0.1627	0.1061	0.2336	0.1893	0.1966	0.1966	0.2309	0.3186	0.1764	0.1295	0.1994	19.94	1.0554			
Detect Signal Activation	0.1563	0.0840	0.1265	0.1061	0.1298	0.1893	0.1966	0.1966	0.0462	0.0637	0.0036	0.3888	0.1406	14.06	1.0610			
Provide Feedback	0.0025	0.0056	0.0060	0.0455	0.1298	0.0379	0.0131	0.0131	0.0330	0.4460	0.0252	0.0432	0.0667	6.67	1.3436			
Operate Throttle, Stick, and Buttons	0.0670	0.1399	0.1265	0.1364	0.1298	0.1893	0.1966	0.1966	0.2309	0.0212	0.0756	0.1295	0.1366	13.66	1.0748			
Sum Total	1	1	1	1	1	1	1	1	1	1	1	1	1	100				

Table 5

List of mission critical targets and metrics

Critical Targets and Metrics		
Function	**Target**	**Metric**
Conform to MIL standard 1472	Fits 95% of aviators	Length, Diameter, Surface Area of throttle & stick
Integrate with Current Lockheed System	Yes	It works with the system
Implement with Various Craft Design	55 separate signals	Number of available signals
Filter and Process I/O Data	Filter noise, process data into appropriate signal type, fast 0ms	Take in data input and output
Output Signals	transfer ≤ 5Gbps of data to Prepar3d	transfer processed data through Output device to computer software
	≤ 10Gbps @ 250 MHz between throttle and stick units	data transfer size and rate
Detect Aircraft Control Intent	< 20 milli seconds	Input latency
Detect Signal Activation	< 20 milli seconds	Input latency

Operate Throttle, Stick and Buttons	Button can be depressed	Measure force required to depress button
	± 35 degrees for stick rotation	Angle of stick
	Throttle travels 6 " or rotates 65°	Distance throttle travels or angle of throttle

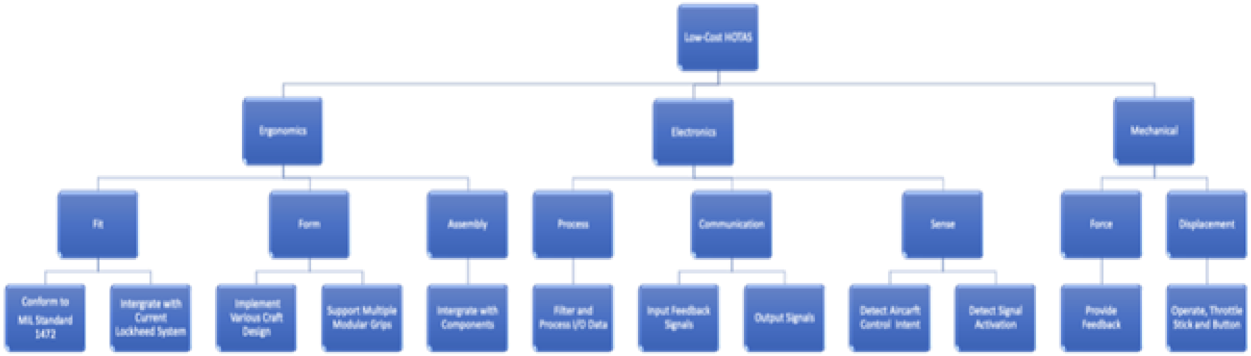
Table 6

Full table catalog of targets and metrics for our project

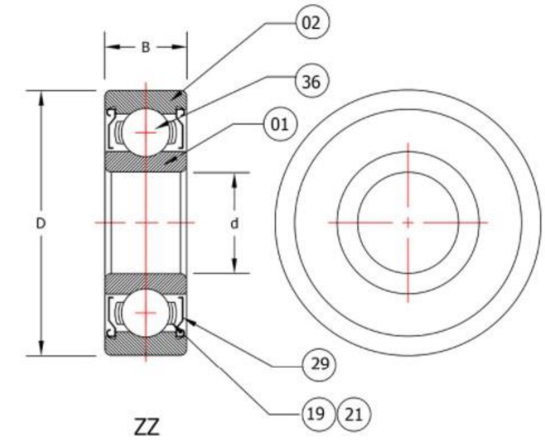
Function	**Target**	**Metric**
Conform to MIL standard 1472	Fits 95% of aviators	Length, Diameter, Surface Area of throttle & stick
Integrate with Current Lockheed System	Yes	It works with the system
Implement with Various Craft Design	55 separate signals	Number of available signals
Support Multiple Modular Grips	Variable per each stick	Major diameter and threading of mounting section for the stick
	1”-2"	Length of mounting section for the stick
	¼"-20	Pitch of the mounting threads for the stick
Integrate Buttons Within Specified Tolerances	±0.078-0.25in (2-6mm)	Distance button can be displaced
Filter and Process I/O Data	Filter noise, process data into appropriate signal type, fast 0ms	Take in data input and output
Input Feedback Signals	Receive signal for AOA, and craft speed to send to process into feedback	Receive data through USB to USB-A
Output Signals	transfer ≤ 5Gbps of data to Prepar3d	transfer processed data through Output device to computer software

	≤ 10Gbps @ 250 MHz between throttle and stick units	data transfer size and rate
Detect Aircraft Control Intent	< 20 milli seconds	Input latency
Detect Signal Activation	< 20 milli seconds	Input latency
Provide Feedback	1.12 ± 0.45 lbf (5 ± 2 N) of force	Provide an actuator force
Operate Throttle, Stick and Buttons	Button can be depressed	Measure force required to depress button
	± 35 degrees for stick rotation	Angle of Stick
	Throttle travels 6 " or rotates 65°	Distance throttle travels or angle of throttle
This one and each below have no function to create a target and metric from	Less than $4000 to manufacture	Cost in $$
	10 lbs. (45 N) ≤ weight ≤ 15 lbs. (67 N)	Weight
	Can be dropped from a height of 29" (73.66 cm) ± 1" (2.54 cm) at any orientation without mechanical failure	Drop height until failure
	At least 2 Years	Component Lifetime
	At least 5 years	Product Lifetime

Figure 1. The figure below shows the different systems and minor functions of our project in a flow chart.


Low-Cost HOTAS
Ergonomics
Electronics
Mechanical
Fit
Form
Assembly
Process
Communication
Sense
Force
Displacement
Conform to MIL Standard 1472
Intergrate with Current Lockheed System
Implement Various Craft Design
Support Multiple Modular Grips
Intergrate with Components
Filter and Process I/O Data
Input Feedback Signals
Output Signals
Detect Aircarft Control Intent
Detect Signal Activation
Provide Feedback
Operate, Throttle Stick and Button

Appendix C Drawings



DIM.	INCH	INCH TOL. +	INCH TOL. -	mm	METRIC TOL. +	METRIC TOL. -
d	0.7500	0	0.0003	19.0500	0	0.008
D	1.6250	0	0.0004	41.2751	0	0.01
B	0.5000	0	0.0047	12.7000	0	0.12

DATE	DRAWN BY	APPROVED BY	APPROVED BY
04/13/21	ST/CG	MM	

This document must not be copied without written premission. The contents must not be issued to a third party, or be used for any unauthorized purposes.

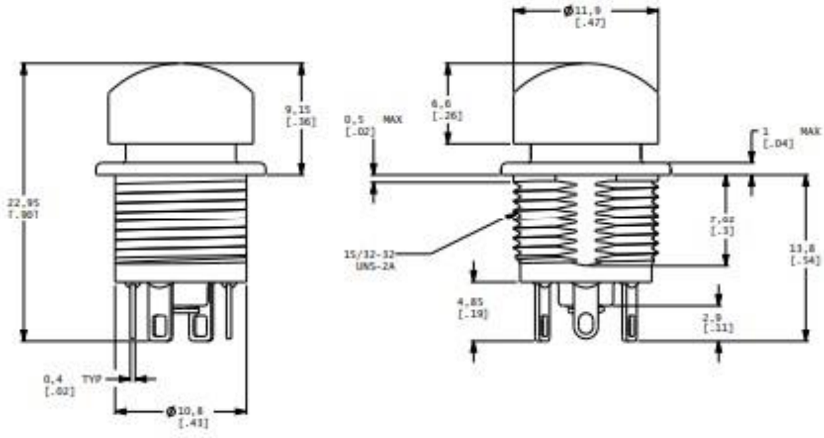
Drawing No.
TRITAN10287ZZ-016

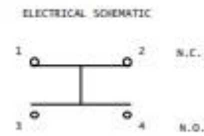
NOTES
ABEC 1
Grease: Mobil Polyrex EM, 30-40% free volume fill
Basic Dynamic Load Rating Cr: 2109 Lbf (9.3813 kN)
Basic Static Load Rating Cor: 1150 Lbf (5.1155 kN)
Radial Internal Clearance - (C0): +0.0002 to -0.0008 inch (+0.005 to -0.02 mm)

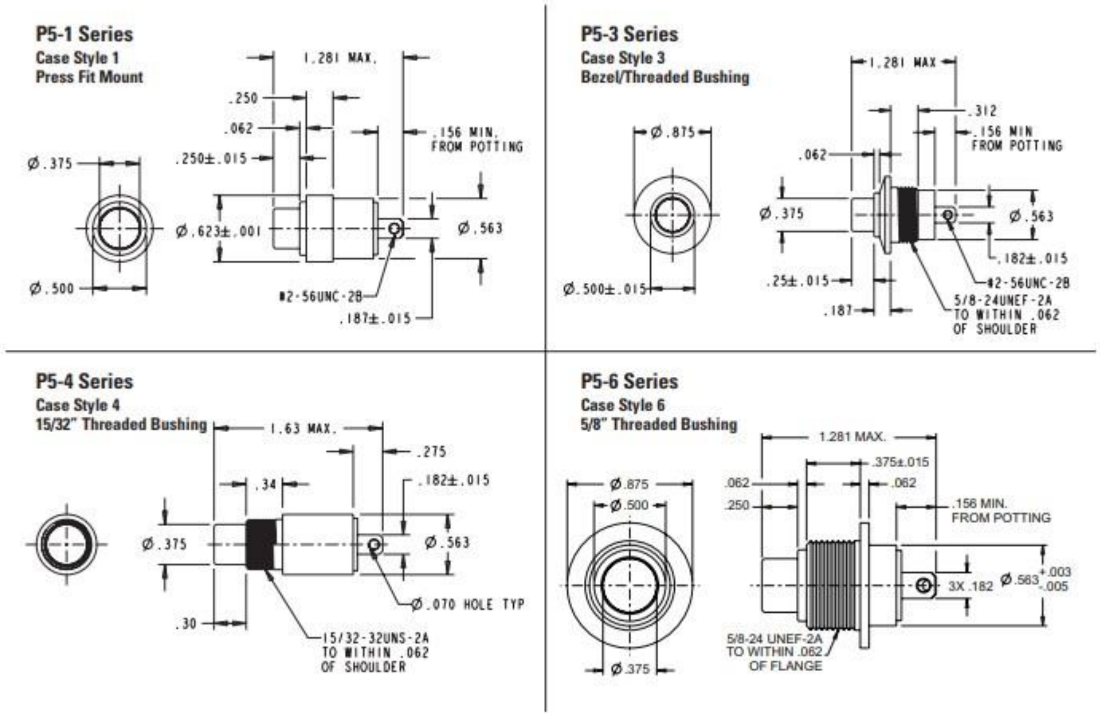
ITEM	COMPONENTS	QTY	MATERIAL	HARDNESS	COMMENTS
01	Inner Ring	1	AISI 52100	60-64 HRc	
02	Outer Ring	1	AISI 52100	60-64 HRc	
36	Balls		AISI 52100	60-64 HRc	
19	Retainer	2	8F		
21	Rivets		AISI 1020		
29	Shields	2	AISI 1020	25-30 HRc	

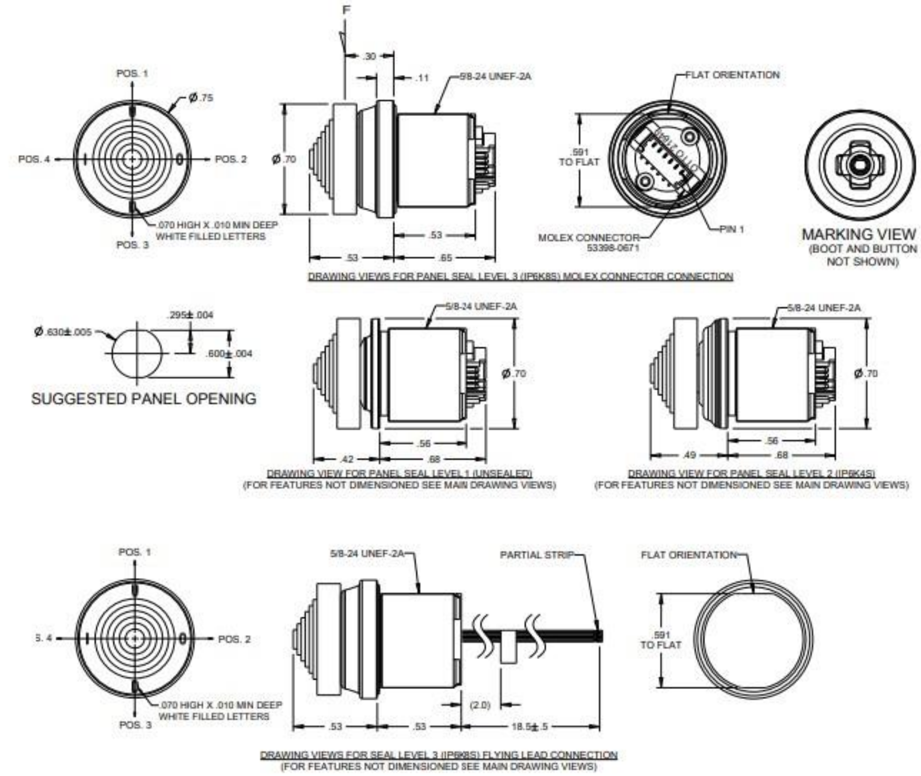
TRITAN®
PRECISION POWER TRANSMISSION COMPONENTS
2100 Pacific St
Hauppauge, NY 11788
www.tritanpt.com

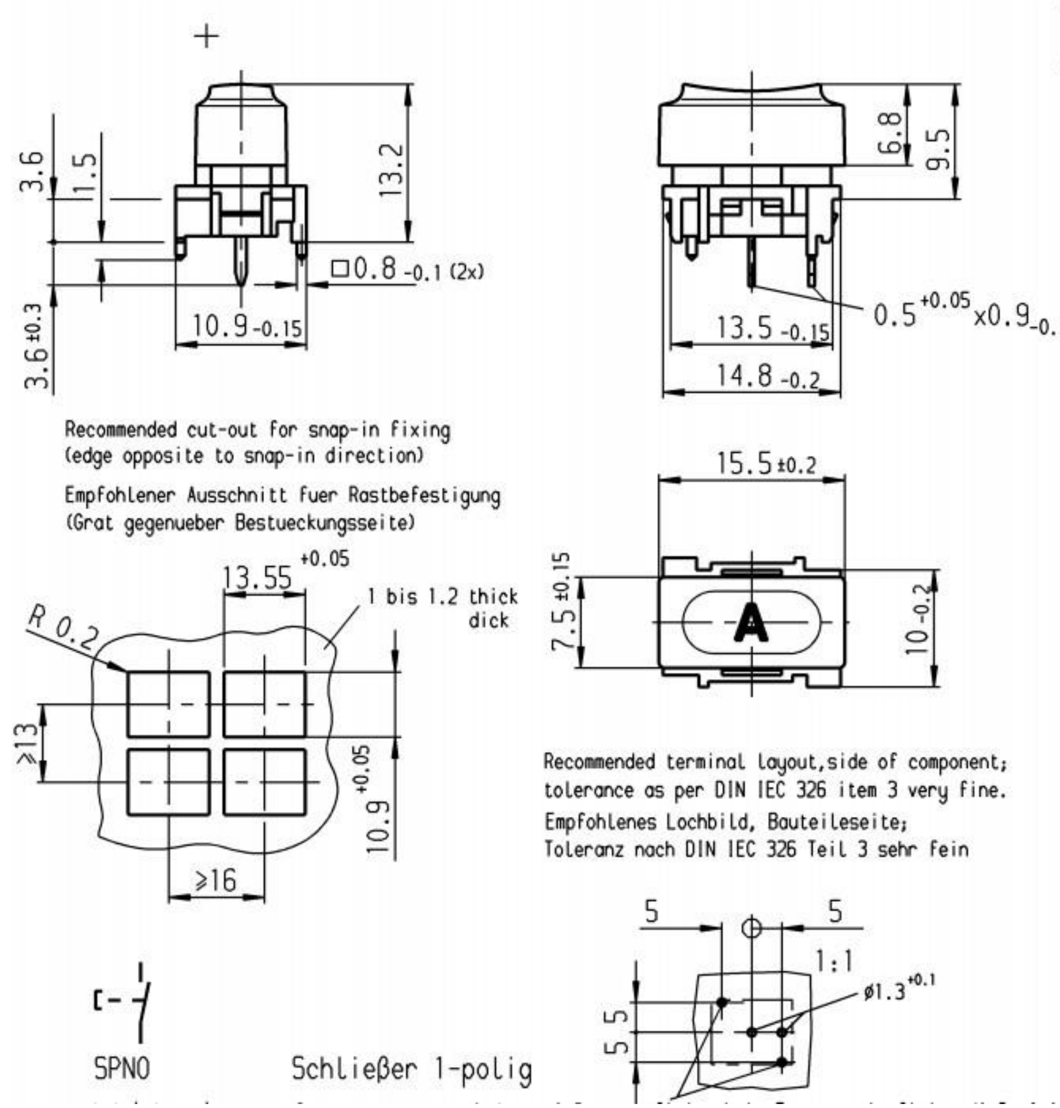
Part Number
1630 ZZ PRX


Ø11,9
[.47]
9,15
[.36]
0,5 MAX
[.02]
6,6
[.26]
1 MAX
[.04]
22,95
[.90]
15/32-32
UNS-2A
[.3]
13,8
[.54]
4,85
[.19]
2,9
[.11]
0,4 TYP
[.02]
Ø10,8
[.43]


ELECTRICAL SCHEMATIC
1
2
N.C.
3
4
N.O.


P5-1 Series
Case Style 1
Press Fit Mount
1.281 MAX.
.250
.062
.250±.015
.156 MIN. FROM POTTING
Ø.375
Ø.623±.001
Ø.563
Ø.500
#2-56UNC-2B
.187±.015
P5-3 Series
Case Style 3
Bezel/Threaded Bushing
1.281 MAX
.312
.156 MIN FROM POTTING
Ø.875
.062
Ø.375
Ø.563
.182±.015
#2-56UNC-2B
Ø.500±.015
.25±.015
.187
5/8-24UNEF-2A TO WITHIN .062 OF SHOULDER
P5-4 Series
Case Style 4
15/32" Threaded Bushing
1.63 MAX.
.275
.34
.182±.015
Ø.375
Ø.563
Ø.070 HOLE TYP
.30
15/32-32UNS-2A TO WITHIN .062 OF SHOULDER
P5-6 Series
Case Style 6
5/8" Threaded Bushing
1.281 MAX.
.375±.015
Ø.875
.062
.062
Ø.500
.250
.156 MIN. FROM POTTING
3X .182
Ø.563 +.003 -.005
5/8-24 UNEF-2A TO WITHIN .062 OF FLANGE
Ø.375

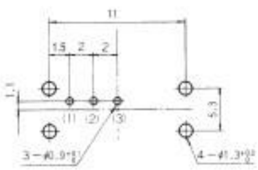

POS. 1
POS. 2
POS. 3
POS. 4
.070 HIGH X .010 MIN DEEP
WHITE FILLED LETTERS
5/8-24 UNEF-2A
FLAT ORIENTATION
.591
TO FLAT
MOLEX CONNECTOR
53398-0671
PIN 1
MARKING VIEW
(BOOT AND BUTTON
NOT SHOWN)
DRAWING VIEWS FOR PANEL SEAL LEVEL 3 (IP6K8S) MOLEX CONNECTOR CONNECTION
SUGGESTED PANEL OPENING
DRAWING VIEW FOR PANEL SEAL LEVEL 1 (UNSEALED)
(FOR FEATURES NOT DIMENSIONED SEE MAIN DRAWING VIEWS)
DRAWING VIEW FOR PANEL SEAL LEVEL 2 (IP6K4S)
(FOR FEATURES NOT DIMENSIONED SEE MAIN DRAWING VIEWS)
PARTIAL STRIP
DRAWING VIEWS FOR SEAL LEVEL 3 (IP6K8S) FLYING LEAD CONNECTION
(FOR FEATURES NOT DIMENSIONED SEE MAIN DRAWING VIEWS)

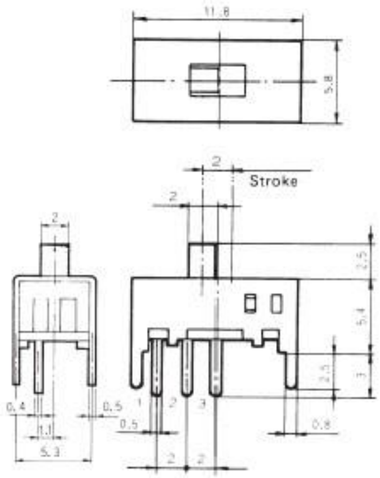

3.6
1.5
13.2
3.6 ±0.3
10.9 -0.15
□0.8 -0.1 (2x)
6.8
9.5
13.5 -0.15
14.8 -0.2
0.5 +0.05 x0.9 -0.1
Recommended cut-out for snap-in fixing
(edge opposite to snap-in direction)
Empfohlener Ausschnitt fuer Rastbefestigung
(Grat gegenueber Bestueckungsseite)
13.55 +0.05
1 bis 1.2 thick
dick
R 0.2
≥13
10.9 +0.05
≥16
15.5 ±0.2
7.5 ±0.15
10 -0.2
A
Recommended terminal layout, side of component;
tolerance as per DIN IEC 326 item 3 very fine.
Empfohlenes Lochbild, Bauteileseite;
Toleranz nach DIN IEC 326 Teil 3 sehr fein
5
5
1:1
ø1.3 +0.1
5
5
SPNO
Schließer 1-polig

MFS101D-8-Z shorting

PC Hole Layouts

(Top view)

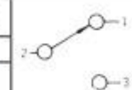




Terminal numbers are not shown on the switch.

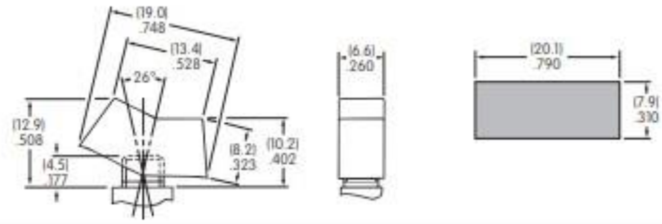
Specifications

Rating	Max.	DC30V 0.3A AC30V 2A (Resistive load)
	Min.	DC5V 10mA (Resistive load)
Initial contact resistance		20mΩ Max.
Dielectric strength		AC500V 1 minute
Insulation resistance		100MΩ Min.
Electrical life		5,000 cycles at DC30V 0.3A 100cycles at AC30V 2A
Operating force		2.45±0.98 N
Switch timing		Shorting

Switching function (Viewed from **A**)		Circuit diagram	No. of terminals
ON	ON		3
2–1	2–3		

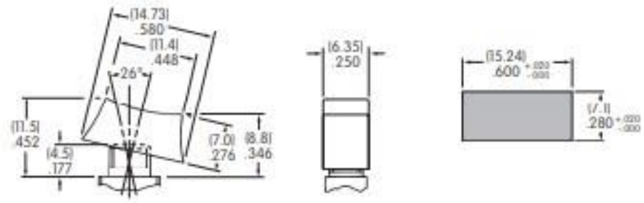
C **AT469**
.260" (6.6mm) Wide Rocker

Antirotational
Material: Polyamide
Colors Available:
A, B, C, E, F, G, H



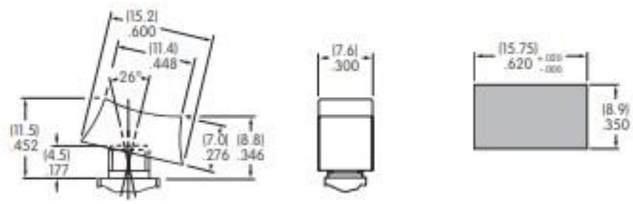
D **AT062**
.250" (6.35mm) Wide Rocker

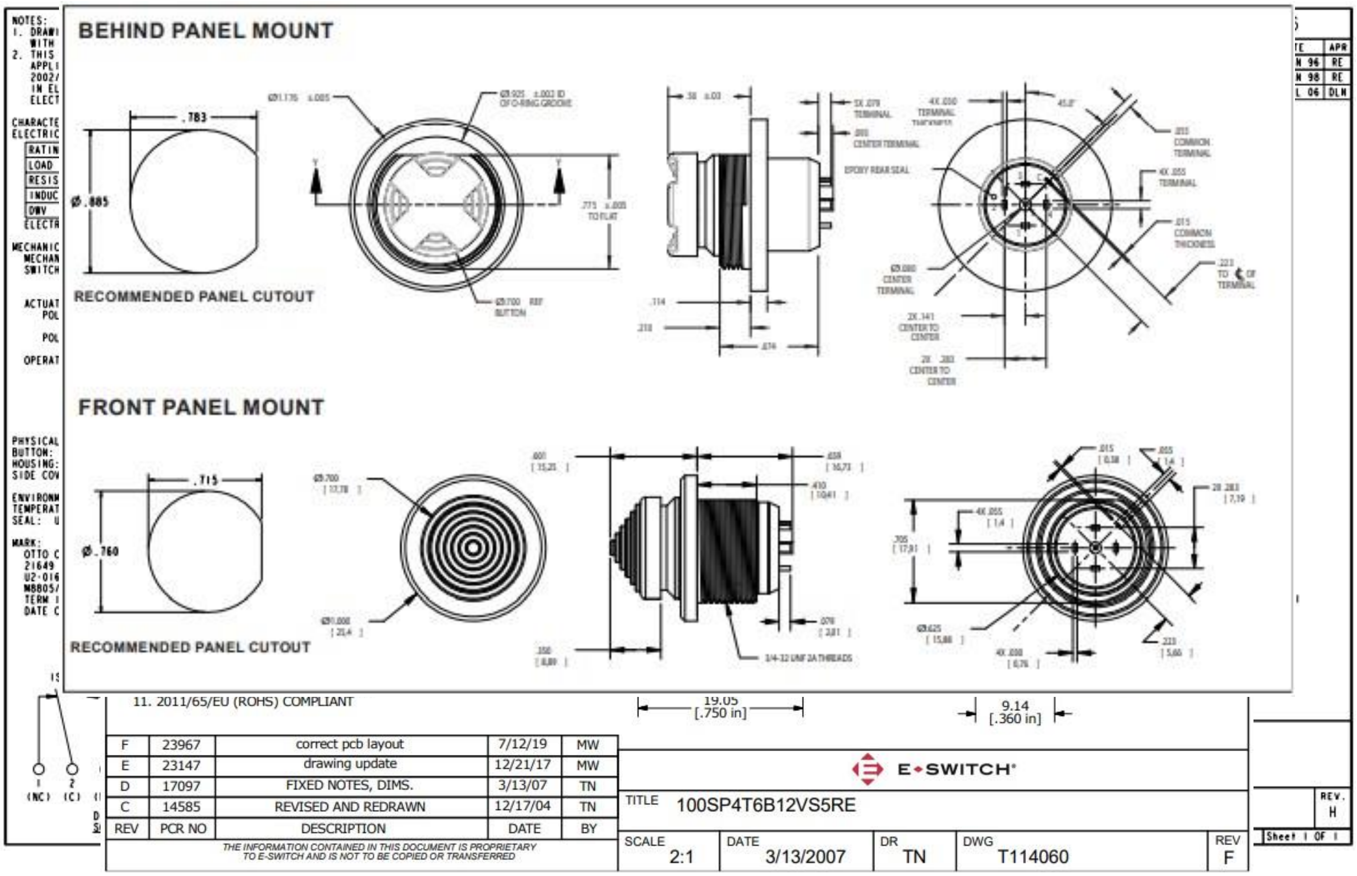
Antirotational
Material: Polyamide
Colors Available:
A, B, C



E **AT066**
.300" (7.6mm) Wide Rocker

Antirotational
Material: Polyamide
Colors Available:
A, B, C

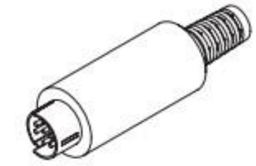



BEHIND PANEL MOUNT
RECOMMENDED PANEL CUTOUT
FRONT PANEL MOUNT
RECOMMENDED PANEL CUTOUT
EPOXY REAR SEAL
3/4-32 UNF 2A THREADS
11. 2011/65/EU (ROHS) COMPLIANT
19.05 [.750 in]
9.14 [.360 in]
F 23967 correct pcb layout 7/12/19 MW
E 23147 drawing update 12/21/17 MW
D 17097 FIXED NOTES, DIMS. 3/13/07 TN
C 14585 REVISED AND REDRAWN 12/17/04 TN
REV PCR NO DESCRIPTION DATE BY
THE INFORMATION CONTAINED IN THIS DOCUMENT IS PROPRIETARY TO E-SWITCH AND IS NOT TO BE COPIED OR TRANSFERRED
E•SWITCH
TITLE 100SP4T6B12VS5RE
SCALE 2:1
DATE 3/13/2007
DR TN
DWG T114060
REV F

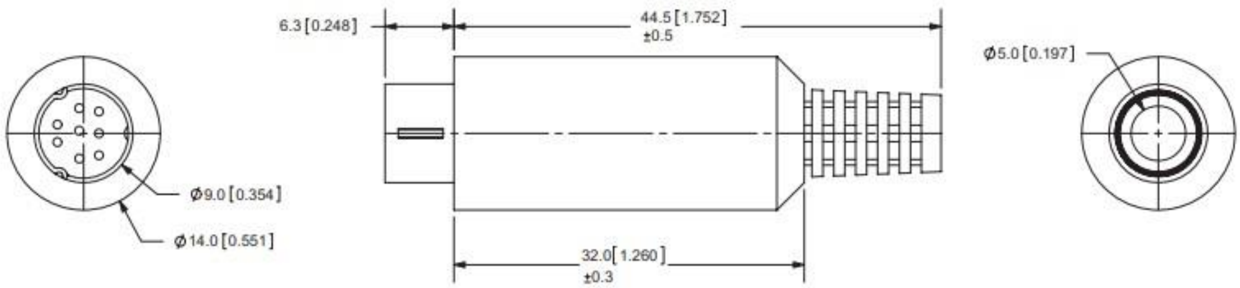
MECHANICAL DRAWINGS

units: mm[inches]

TOLERANCE: ±0.2mm



	MATERIAL	PLATING
shield	brass	nickel
pin contacts (1~9)	brass	silver
insulator	Polyamide 6 (PA-1010C2)	
shell	ABS (PA-757)	
cover	UE630 + PELL (LL120)	

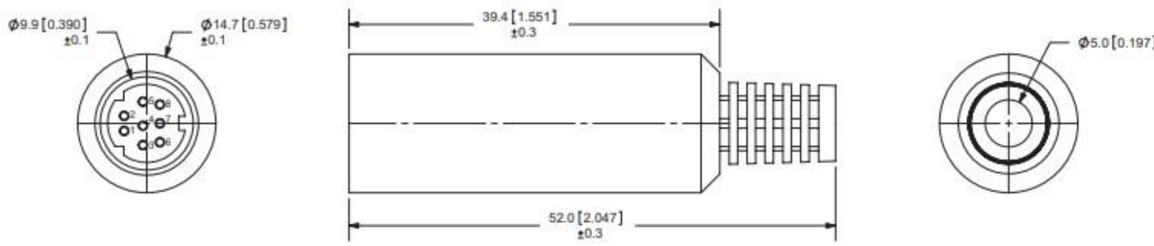


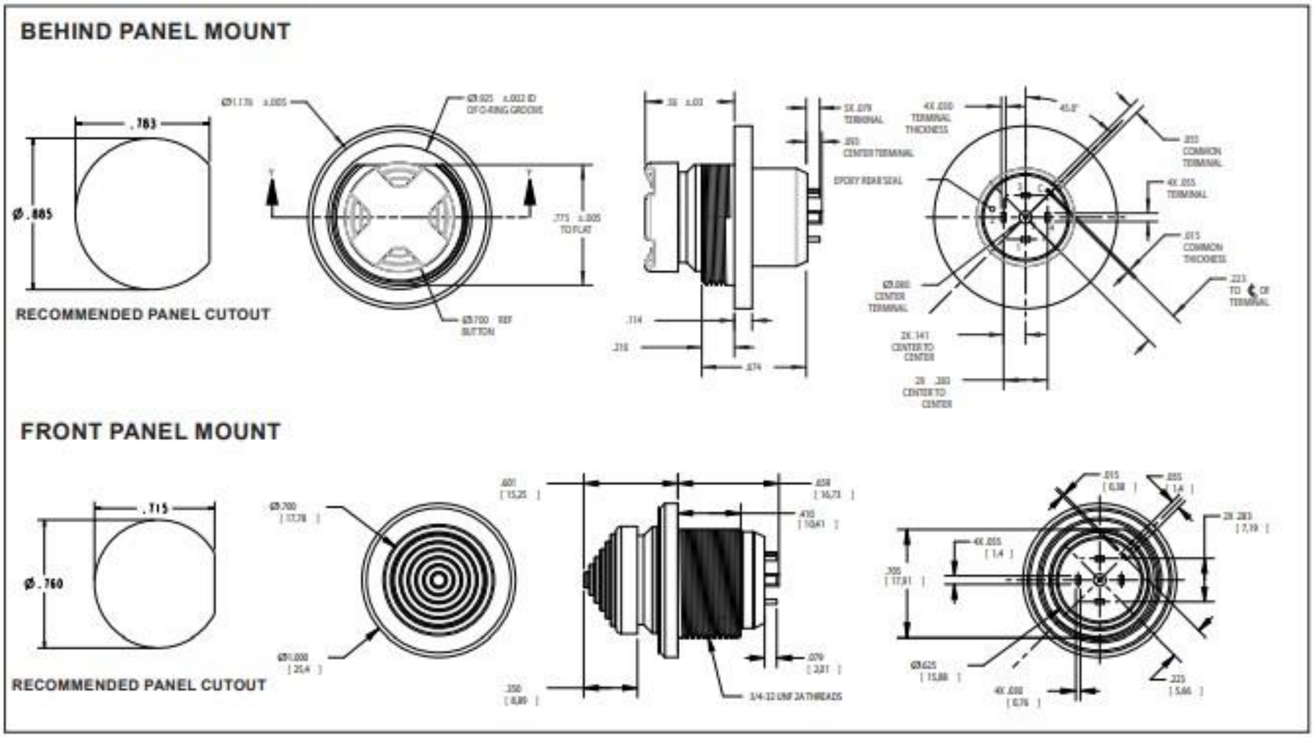
MECHANICAL DRAWINGS

units: mm[inches]

TOLERANCE: ±0.1mm

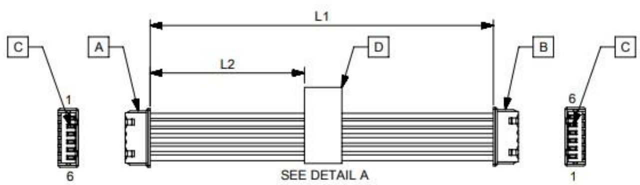
	MATERIAL	PLATING
shell	copper	nickel
pin contacts (1~9)	brass	silver
insulator	Nylon6+glass fiber	
boot	PE + 2L	
hood	ABS (PA-757)	




BEHIND PANEL MOUNT
.783
Ø.885
RECOMMENDED PANEL CUTOUT
FRONT PANEL MOUNT
.715
Ø.760
RECOMMENDED PANEL CUTOUT

ITEM	PART#	DESCRIPTION	QTY	UOM
A,B	510210600	PicoBlade1.25 Rec Hsg 6P	2	PC
C	500588000	PicoBlade1.25 Crimp Rec Term Chain	12	PC
D	887804719	Blank label 12.7x35.5mm (WHT:12.7mm) HF	1	PC

FROM	TO	DESCRIPTION	COLOR
A1	B6	CABLE 28 AWG UL 1061 BLACK	BLACK
A2	B5	CABLE 28 AWG UL 1061 BLACK	BLACK
A3	B4	CABLE 28 AWG UL 1061 BLACK	BLACK
A4	B3	CABLE 28 AWG UL 1061 BLACK	BLACK
A5	B2	CABLE 28 AWG UL 1061 BLACK	BLACK
A6	B1	CABLE 28 AWG UL 1061 BLACK	BLACK

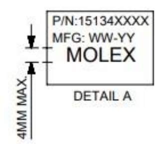


TABLE

PART NUMBER	L1	L2	TITLE
151340600	50±6	20±5	Picoblade 6 Circuit 50MM
151340601	100±6	45±5	Picoblade 6 Circuit 100MM
151340602	150±8	70±5	Picoblade 6 Circuit 150MM
151340603	300±10	145±10	Picoblade 6 Circuit 300MM
151340605	450±10	220±10	Picoblade 6 Circuit 450MM
151340606	600±10	295±10	Picoblade 6 Circuit 600MM

NOTES:

1. Cable assembly to be tested 100% for continuity and polarity.
2. Label text must be 2mm max. In height with Arial font.
3. Connector view shown is from mating side.
4. Label must be wrapped in Flag type.
5. Stick UL label on the outside carton.



DETAIL A

REVISION			
DATE	REV	DESCRIPTION	CHANGER
26/07/2016	A	INITIAL RELEASE	DICK
26/04/2019	B	PROJECT TRANSFER FROM DG TO INDIA	ARAJU
24/06/2019	B1	LABEL CHANGE	ARAJU

QUALITY SYMBOLS: = 0; = 0; = 0; = 0; = 0; = 0; = 0; = 0

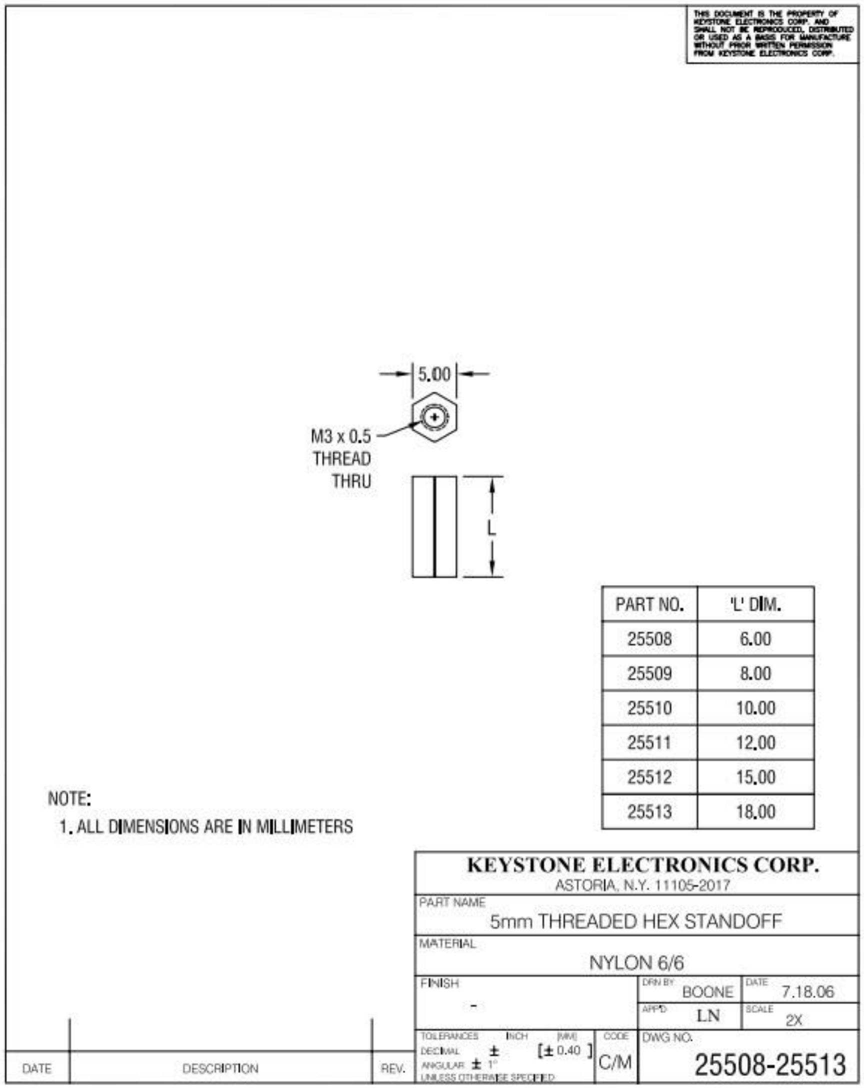
EC NO: 619691 2019/06/11
DRWN: ARAJU 2019/06/26
CHK'D: RDESA401 2019/06/26
APPR: RDESA401
REV B1

GENERAL TOLERANCES (UNLESS SPECIFIED)
ANGULAR TOL ±
4 PLACES ±
3 PLACES ±
2 PLACES ±
1 PLACE ±
0 PLACES ±
DRAFT WHERE APPLICABLE MUST REMAIN WITHIN DIMENSIONS

DIMENSION UNITS: mm | SCALE: NTS
DRWN BY: WLXIE | DATE: 2016/07/12
CHK'D BY: DHUANG16 | DATE: 2016/07/25
APPR BY: YXZOU | DATE: 2016/07/28
DRAWING SIZE: A3 | THIRD ANGLE PROJECTION

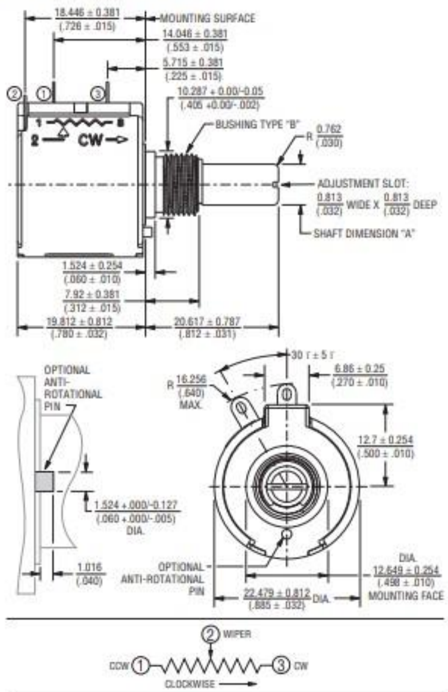
molex
SEE TABLE
PRODUCT CUSTOMER DRAWING
SERIES: 201234 | MATERIAL NUMBER: SEE TABLE | CUSTOMER: GENERAL MARKET
DOCUMENT NUMBER: 2012341358 | DOC TYPE: PSD | DOC PART: 000 | SHEET NUMBER: 1 OF 1

RELEASE STATUS P1 | RELEASE DATE 2019/06/26 04:26:05


THIS DOCUMENT IS THE PROPERTY OF KEYSTONE ELECTRONICS CORP. AND SHALL NOT BE REPRODUCED, DISTRIBUTED OR USED AS A BASIS FOR MANUFACTURE WITHOUT PRIOR WRITTEN PERMISSION FROM KEYSTONE ELECTRONICS CORP.
5.00
M3 x 0.5
THREAD
THRU
L
PART NO.
'L' DIM.
25508
6.00
25509
8.00
25510
10.00
25511
12.00
25512
15.00
25513
18.00
NOTE:
1. ALL DIMENSIONS ARE IN MILLIMETERS
KEYSTONE ELECTRONICS CORP.
ASTORIA, N.Y. 11105-2017
PART NAME
5mm THREADED HEX STANDOFF
MATERIAL
NYLON 6/6
FINISH
-
DRN BY
BOONE
DATE
7.18.06
APP'D
LN
SCALE
2X
TOLERANCES
INCH
[MM]
DECIMAL
±
[± 0.40]
ANGULAR ± 1°
UNLESS OTHERWISE SPECIFIED
CODE
C/M
DWG NO.
25508-25513
DATE
DESCRIPTION
REV.

Product Dimensions

Single Gang, Bushing Mount



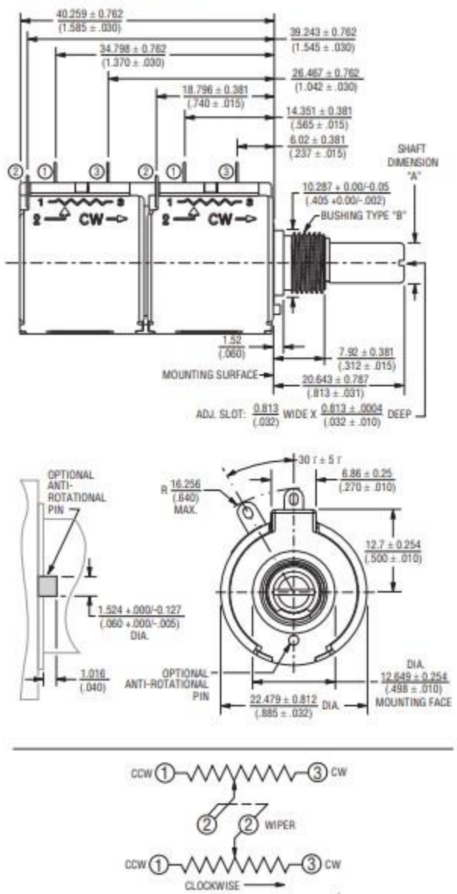
TOLERANCES: EXCEPT WHERE NOTED

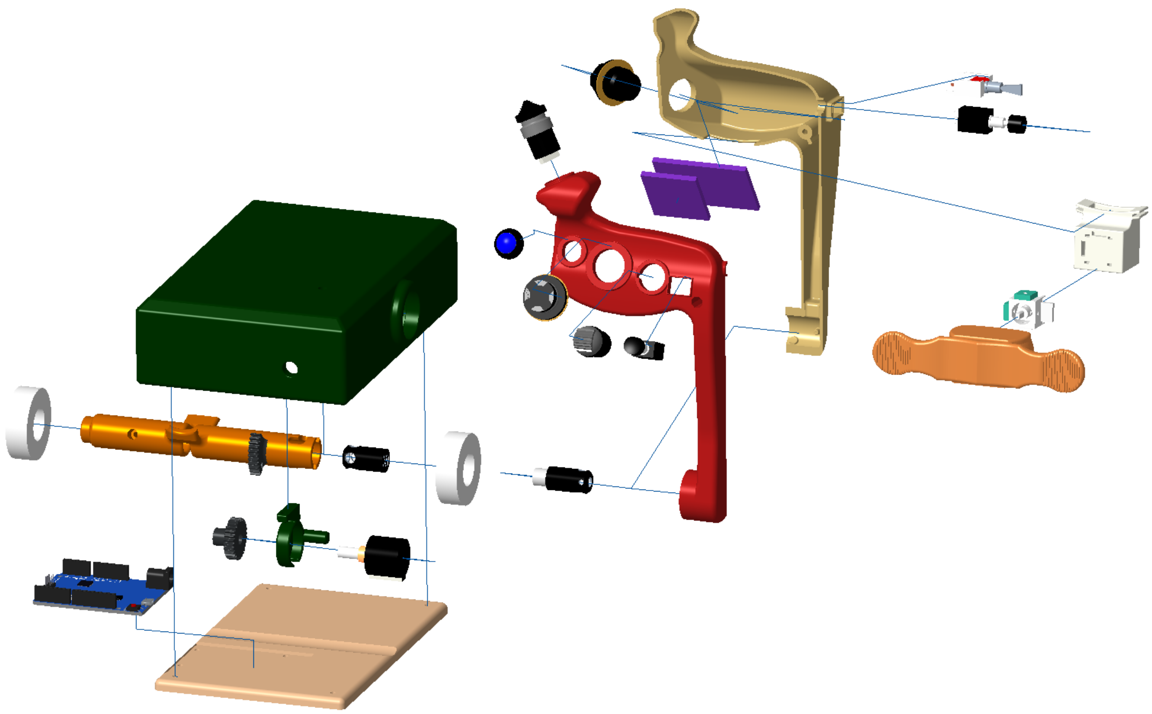
DECIMALS: .XX ± $\frac{.50}{(.02)}$ .XXX ± $\frac{.127}{(.005)}$ .XXXX ± $\frac{.0127}{(.0005)}$

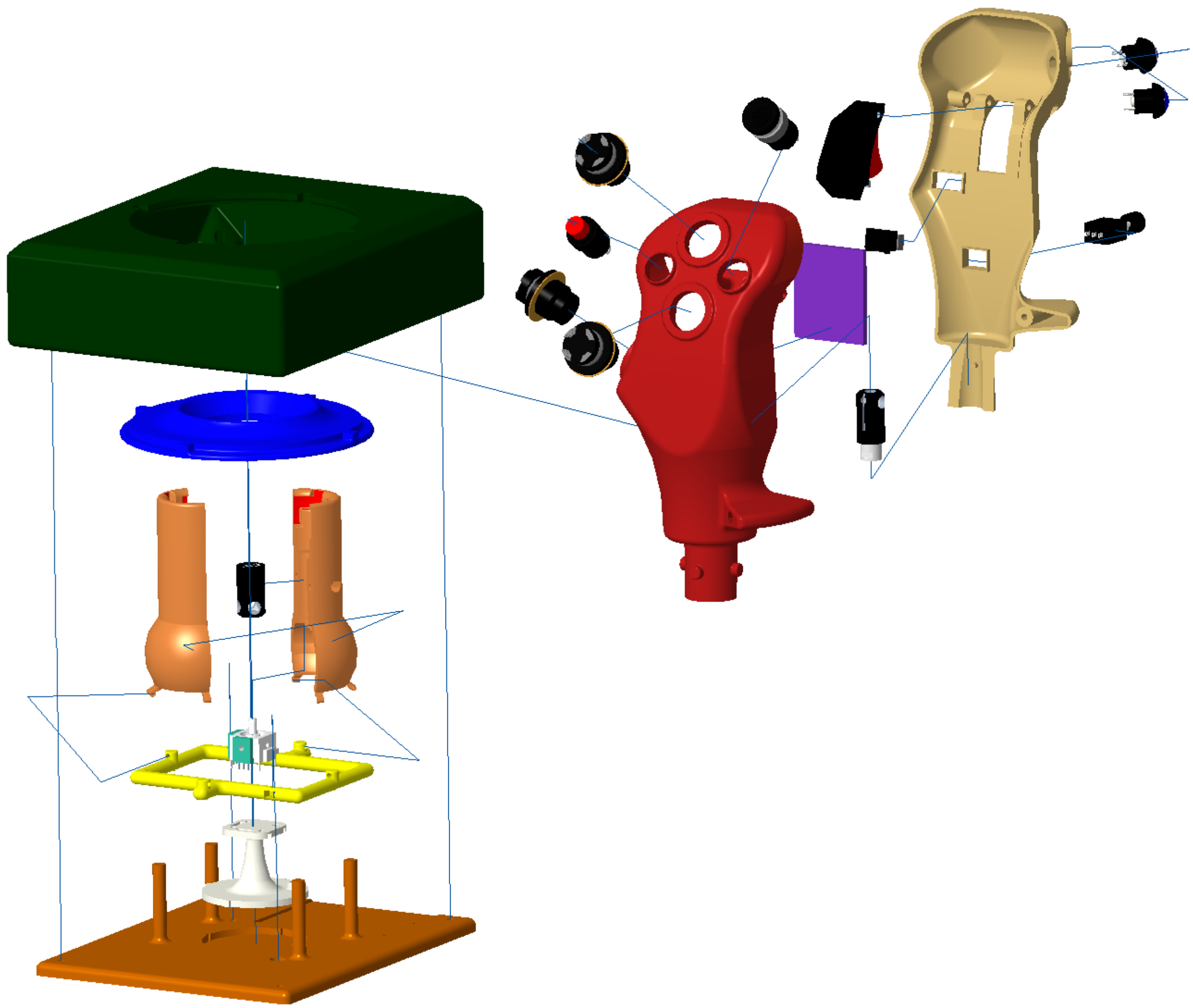
DIMENSIONS: $\frac{MM}{(IN)}$

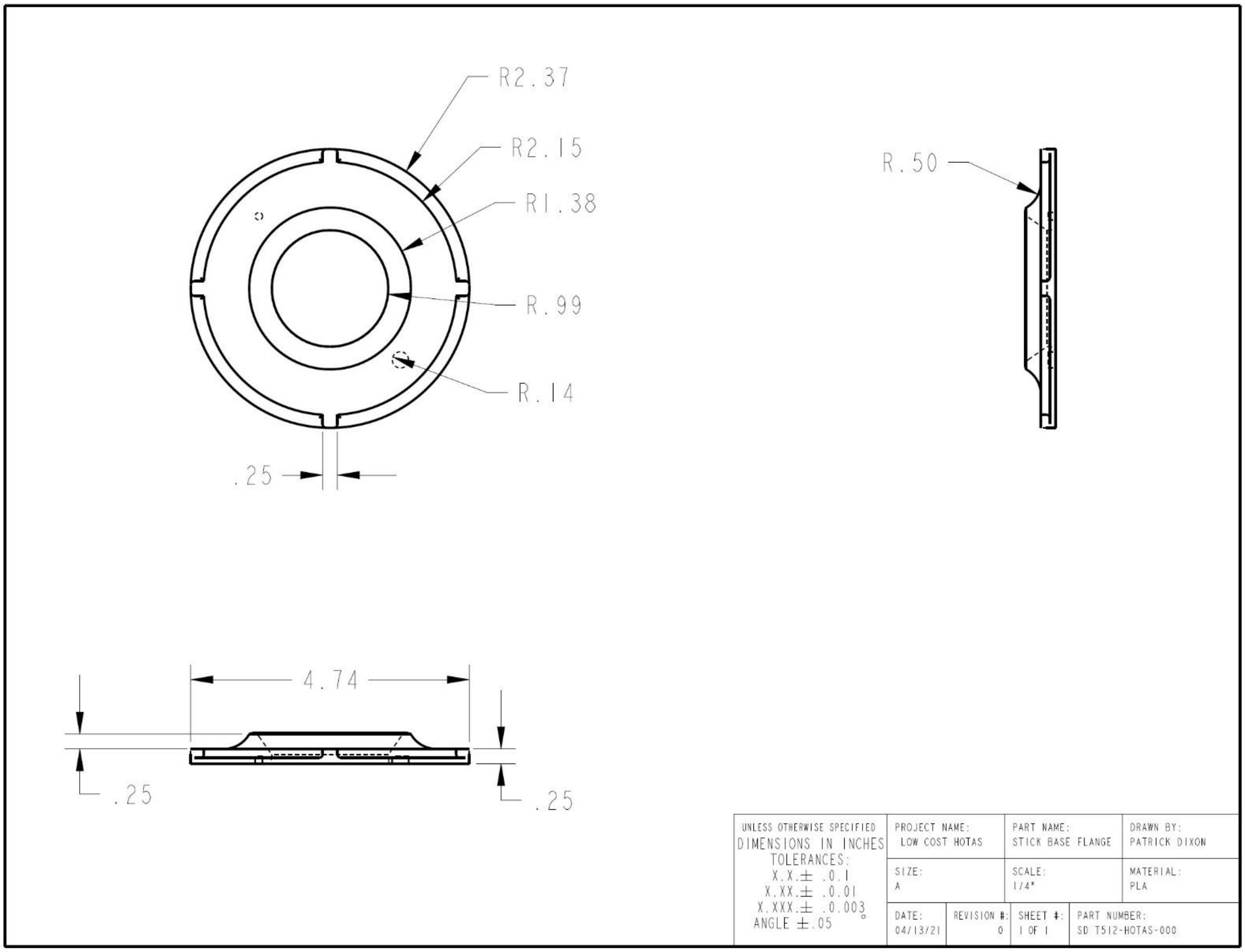
Bushing Selection Code	Shaft Dimension "A"	Shaft Material	Bushing Type "B"	Bushing Material
A	6.34 +0/-0.022 (0.2497 +0/-0.0009)	Nickel Plated Brass	3/8 " 32-UNEF- 2A THD.	Brass
B	6.00 +0/-0.022 (0.2362 +0/-0.0009)	Nickel Plated Brass	M9 X 0.75-8g	Brass
C	6.34 +0/-0.007 (0.2497 +0/-0.0003)	Stainless Steel	3/8 " 32-UNEF- 2A THD.	Bronze
D	6.00 +0/-0.007 (0.2362 +0/-0.0003)	Stainless Steel	M9 X 0.75-8g	Bronze
G	6.34 +0/-0.007 (0.2497 +0/-0.0003)	Stainless Steel	3/8 " 32-UNEF- 2A THD.	Bronze
H	6.00 +0/-0.007 (0.2362 +0/-0.0003)	Stainless Steel	M9 X 0.75-8g	Bronze

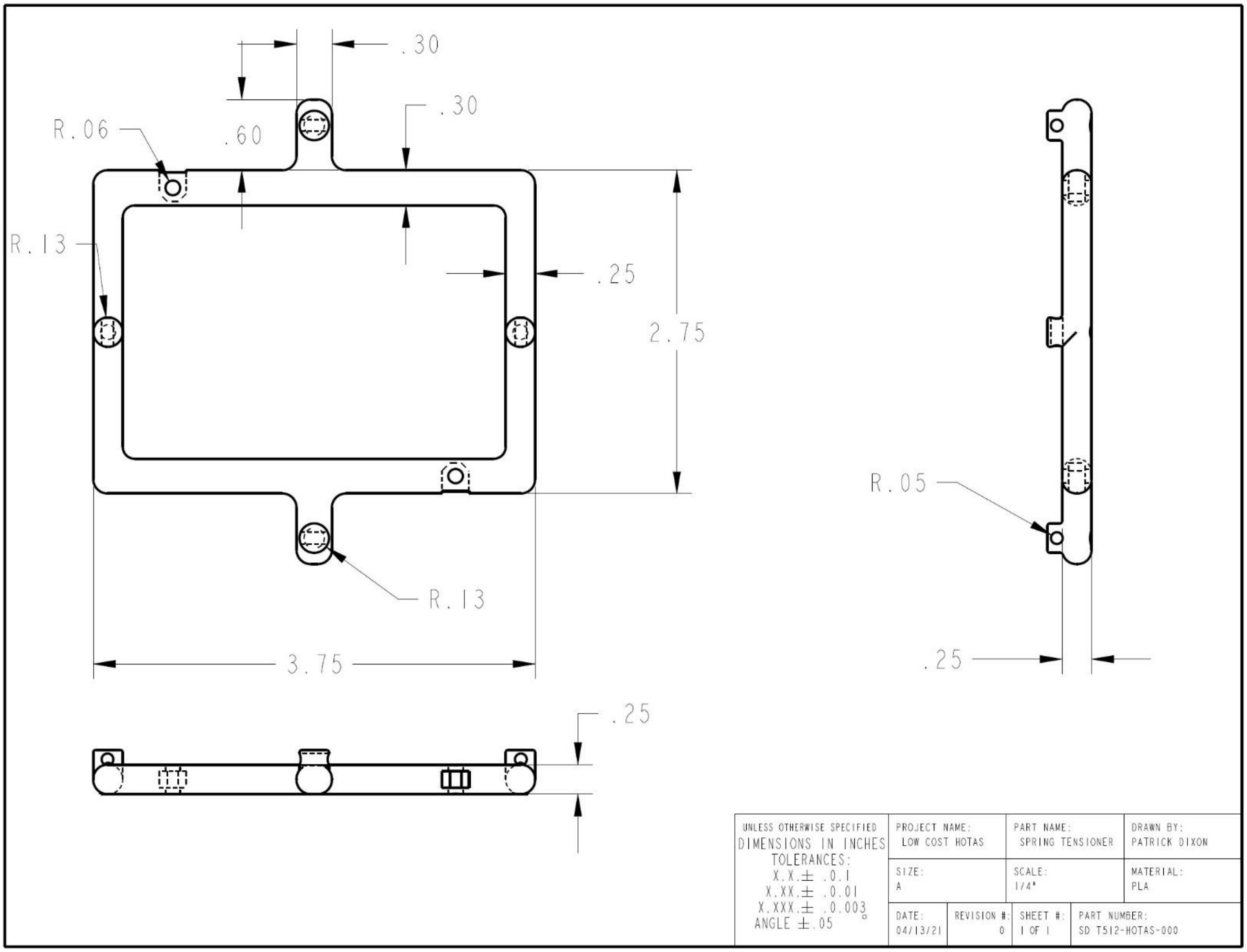
Dual Gang, Bushing Mount

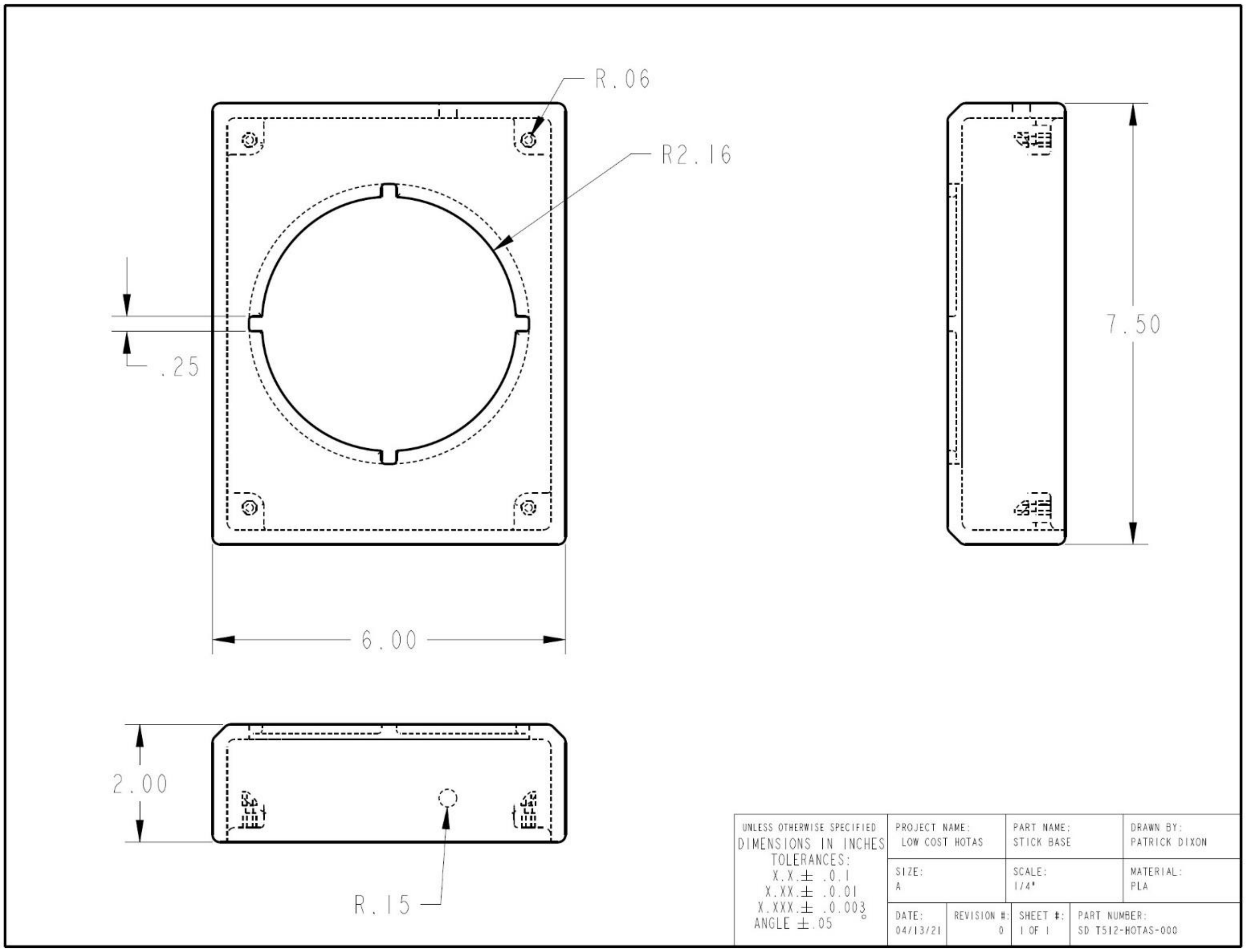


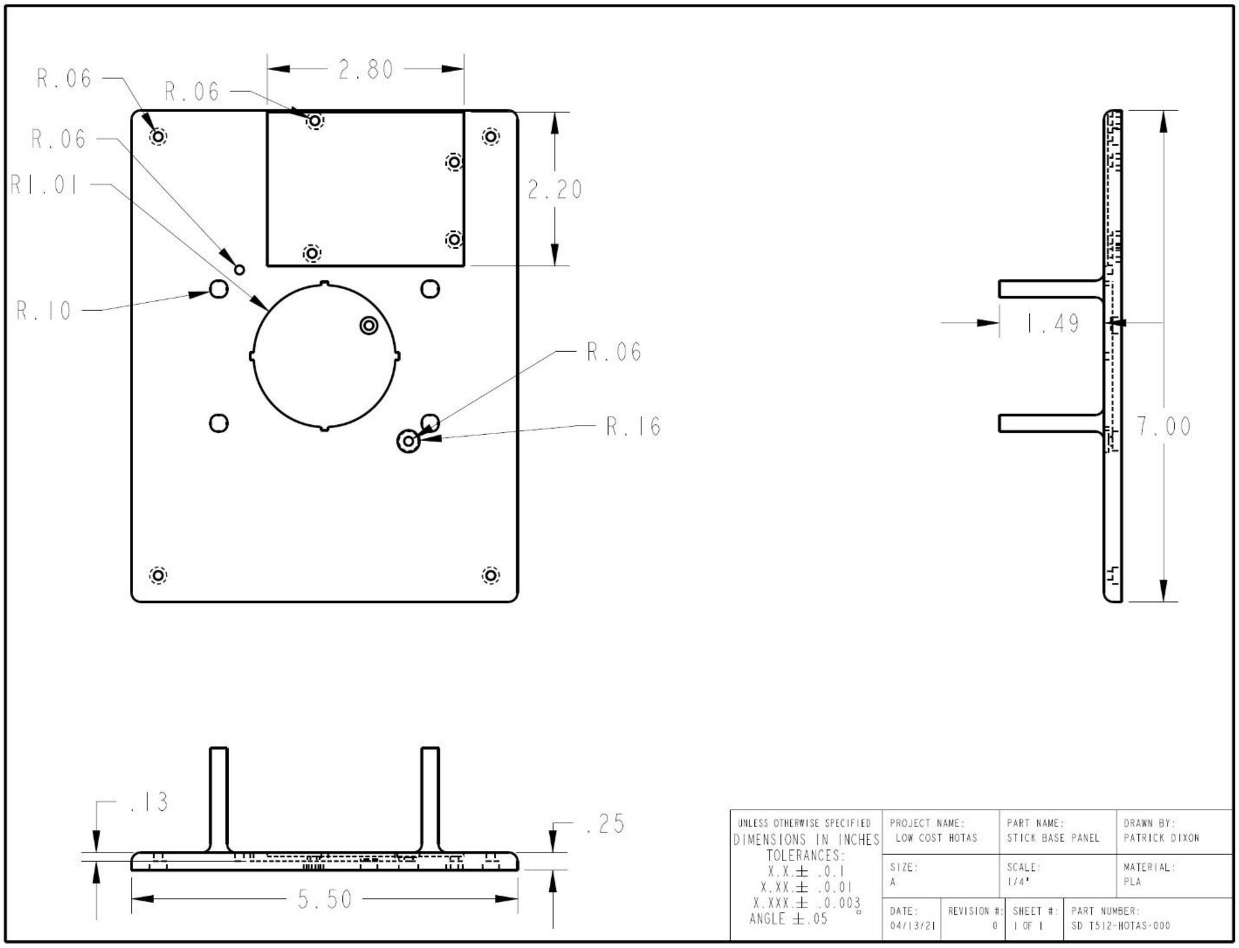




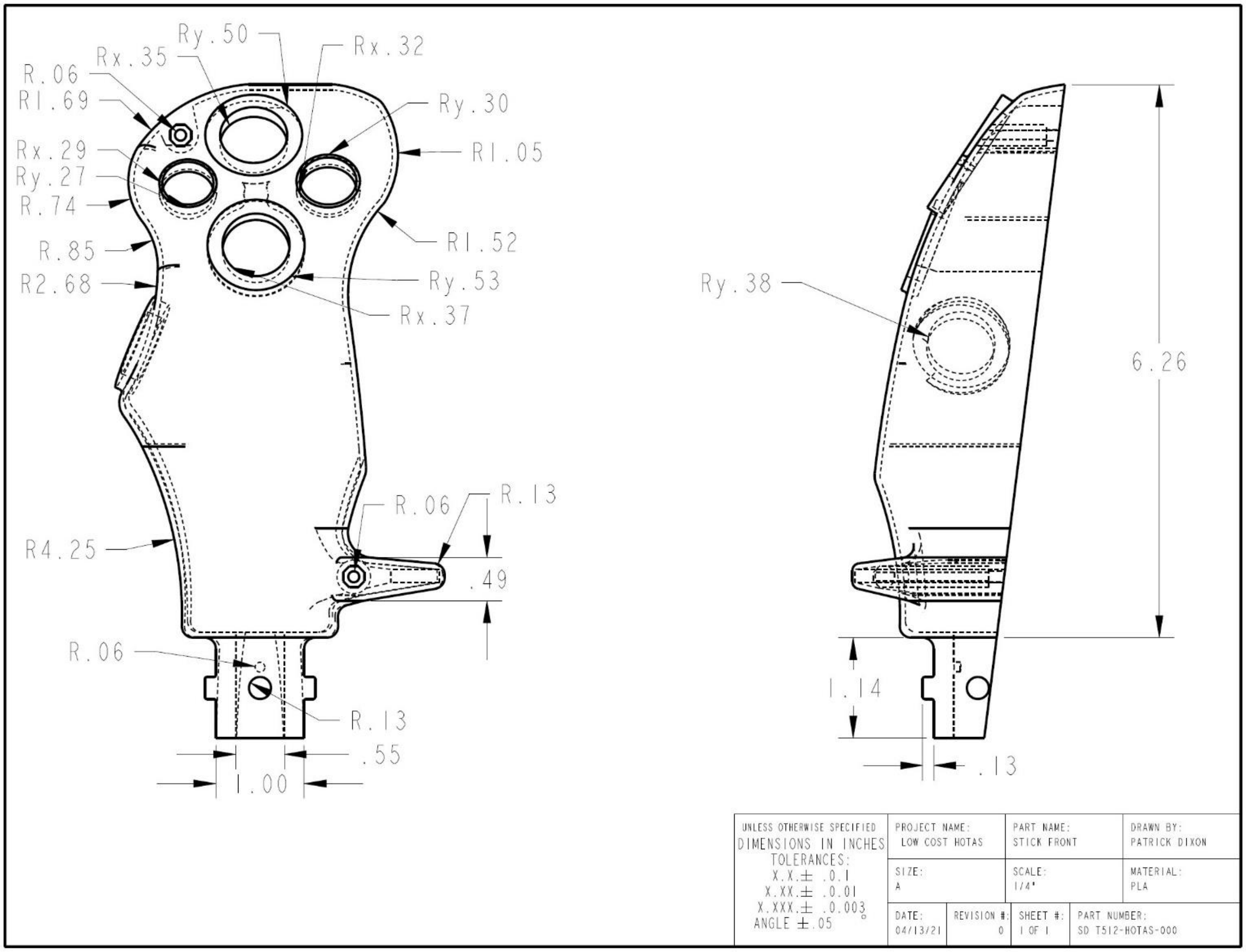

R2.37
R2.15
R1.38
R.99
R.14
.25
R.50
4.74
.25
.25
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X.± .0.1
X.XX.± .0.01
X.XXX.± .0.003
ANGLE ±.05°
PROJECT NAME: LOW COST HOTAS
PART NAME: STICK BASE FLANGE
DRAWN BY: PATRICK DIXON
SIZE: A
SCALE: 1/4"
MATERIAL: PLA
DATE: 04/13/21
REVISION #: 0
SHEET #: 1 OF 1
PART NUMBER: SD T512-HOTAS-000

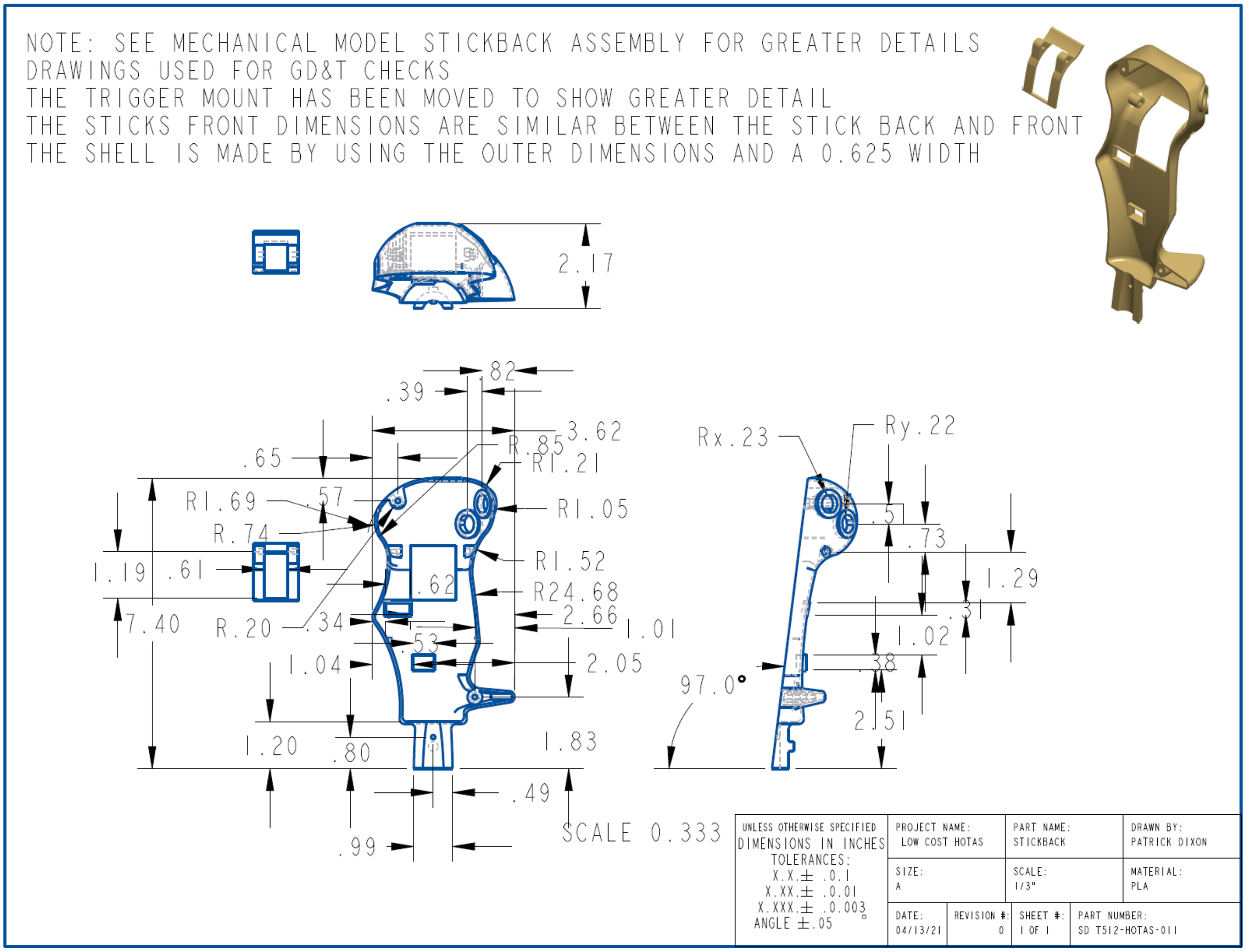

.30
.30
R.06
.60
R.13
.25
2.75
R.05
R.13
3.75
.25
.25
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X.± .0.1
X.XX.± .0.01
X.XXX.± .0.003
ANGLE ±.05°
PROJECT NAME: LOW COST HOTAS
PART NAME: SPRING TENSIONER
DRAWN BY: PATRICK DIXON
SIZE: A
SCALE: 1/4"
MATERIAL: PLA
DATE: 04/13/21
REVISION #: 0
SHEET #: 1 OF 1
PART NUMBER: SD T512-HOTAS-000

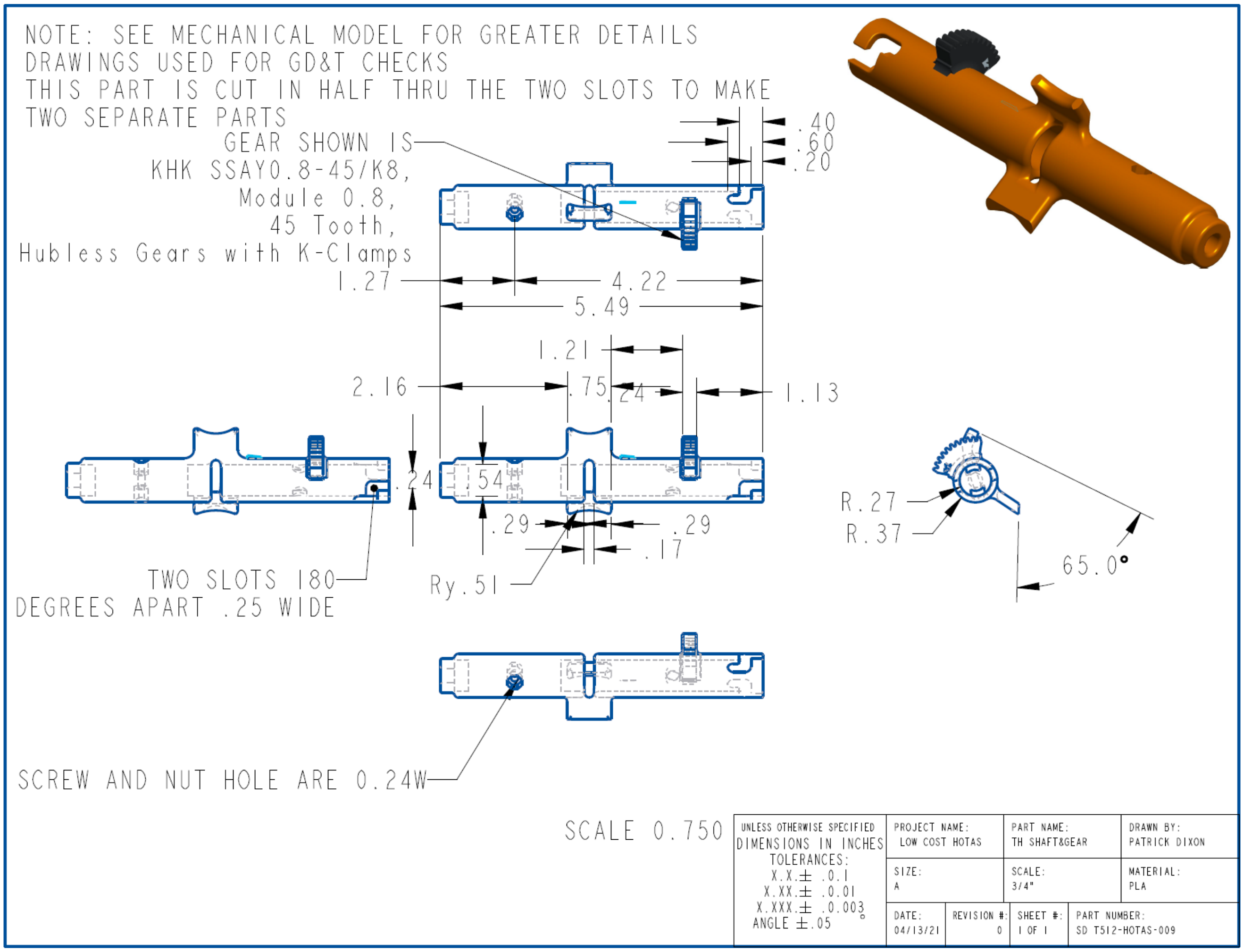

R.06
R2.16
.25
7.50
6.00
2.00
R.15
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X ± .0.1
X.XX ± .0.01
X.XXX ± .0.003
ANGLE ± .05°
PROJECT NAME: LOW COST HOTAS
PART NAME: STICK BASE
DRAWN BY: PATRICK DIXON
SIZE: A
SCALE: 1/4"
MATERIAL: PLA
DATE: 04/13/21
REVISION #: 0
SHEET #: 1 OF 1
PART NUMBER: SD T512-HOTAS-000



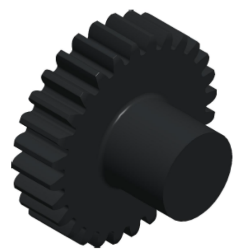
2.80
R.06
R.06
R.06
R1.01
2.20
R.10
R.06
R.16
1.49
7.00
.13
.25
5.50
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X ± .0.1
X.XX ± .0.01
X.XXX ± .0.003
ANGLE ± .05
PROJECT NAME: LOW COST HOTAS
PART NAME: STICK BASE PANEL
DRAWN BY: PATRICK DIXON
SIZE: A
SCALE: 1/4"
MATERIAL: PLA
DATE: 04/13/21
REVISION #: 0
SHEET #: 1 OF 1
PART NUMBER: SD T512-HOTAS-000


Ry.50
Rx.35
Rx.32
R.06
R1.69
Ry.30
Rx.29
R1.05
Ry.27
R.74
R1.52
R.85
Ry.53
R2.68
Rx.37
Ry.38
6.26
R.06
R.13
R4.25
.49
R.06
1.14
R.13
.55
.13
1.00
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X.± .0.1
X.XX.± .0.01
X.XXX.± .0.003
ANGLE ±.05°
PROJECT NAME: LOW COST HOTAS
PART NAME: STICK FRONT
DRAWN BY: PATRICK DIXON
SIZE: A
SCALE: 1/4"
MATERIAL: PLA
DATE: 04/13/21
REVISION #: 0
SHEET #: 1 OF 1
PART NUMBER: SD T512-HOTAS-000

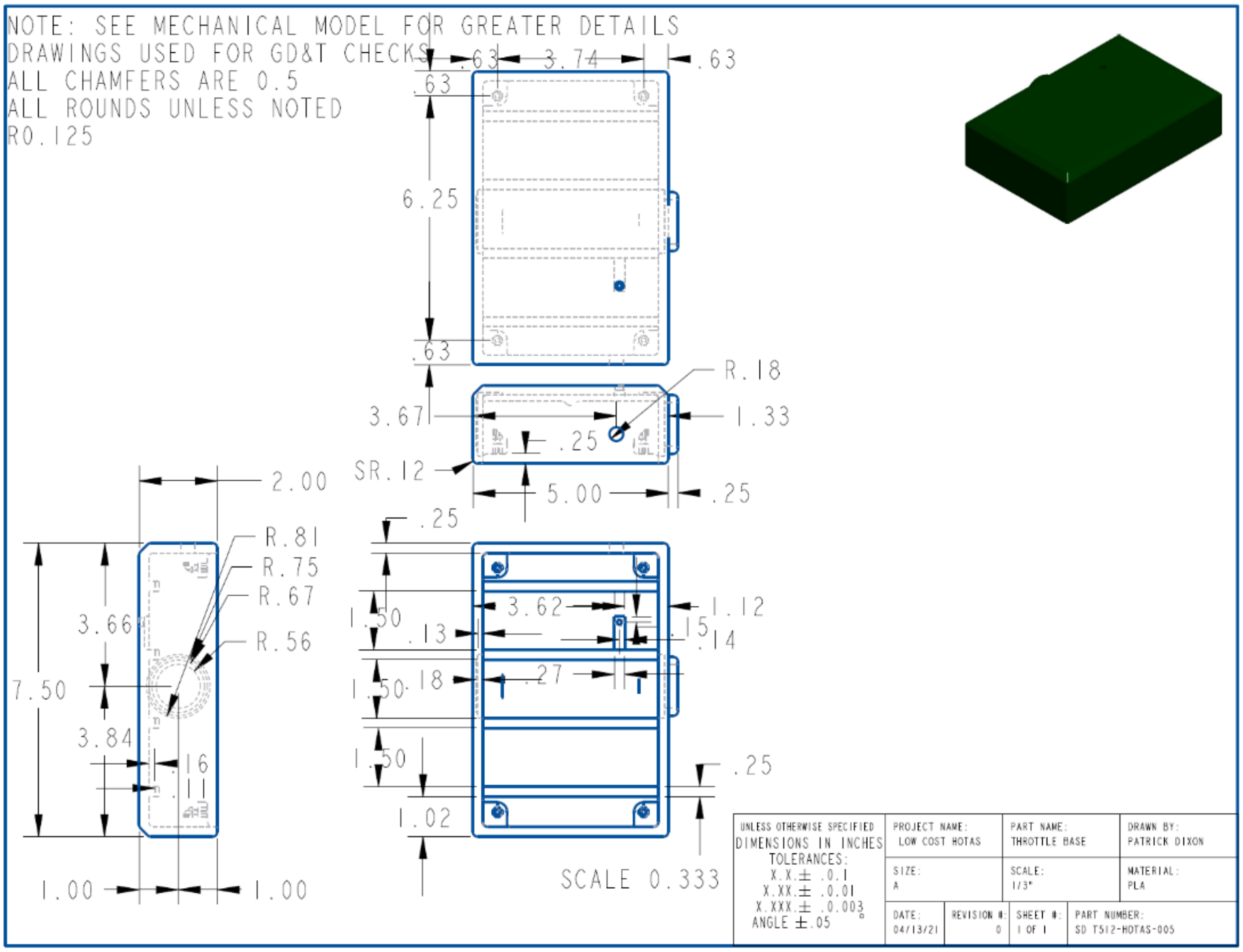

NOTE: SEE MECHANICAL MODEL STICKBACK ASSEMBLY FOR GREATER DETAILS
DRAWINGS USED FOR GD&T CHECKS
THE TRIGGER MOUNT HAS BEEN MOVED TO SHOW GREATER DETAIL
THE STICKS FRONT DIMENSIONS ARE SIMILAR BETWEEN THE STICK BACK AND FRONT
THE SHELL IS MADE BY USING THE OUTER DIMENSIONS AND A 0.625 WIDTH
SCALE 0.333
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X.± .0.1
X.XX.± .0.01
X.XXX.± .0.003
ANGLE ±.05°
PROJECT NAME: LOW COST HOTAS
PART NAME: STICKBACK
DRAWN BY: PATRICK DIXON
SIZE: A
SCALE: 1/3"
MATERIAL: PLA
DATE: 04/13/21
REVISION #: 0
SHEET #: 1 OF 1
PART NUMBER: SD T512-HOTAS-011

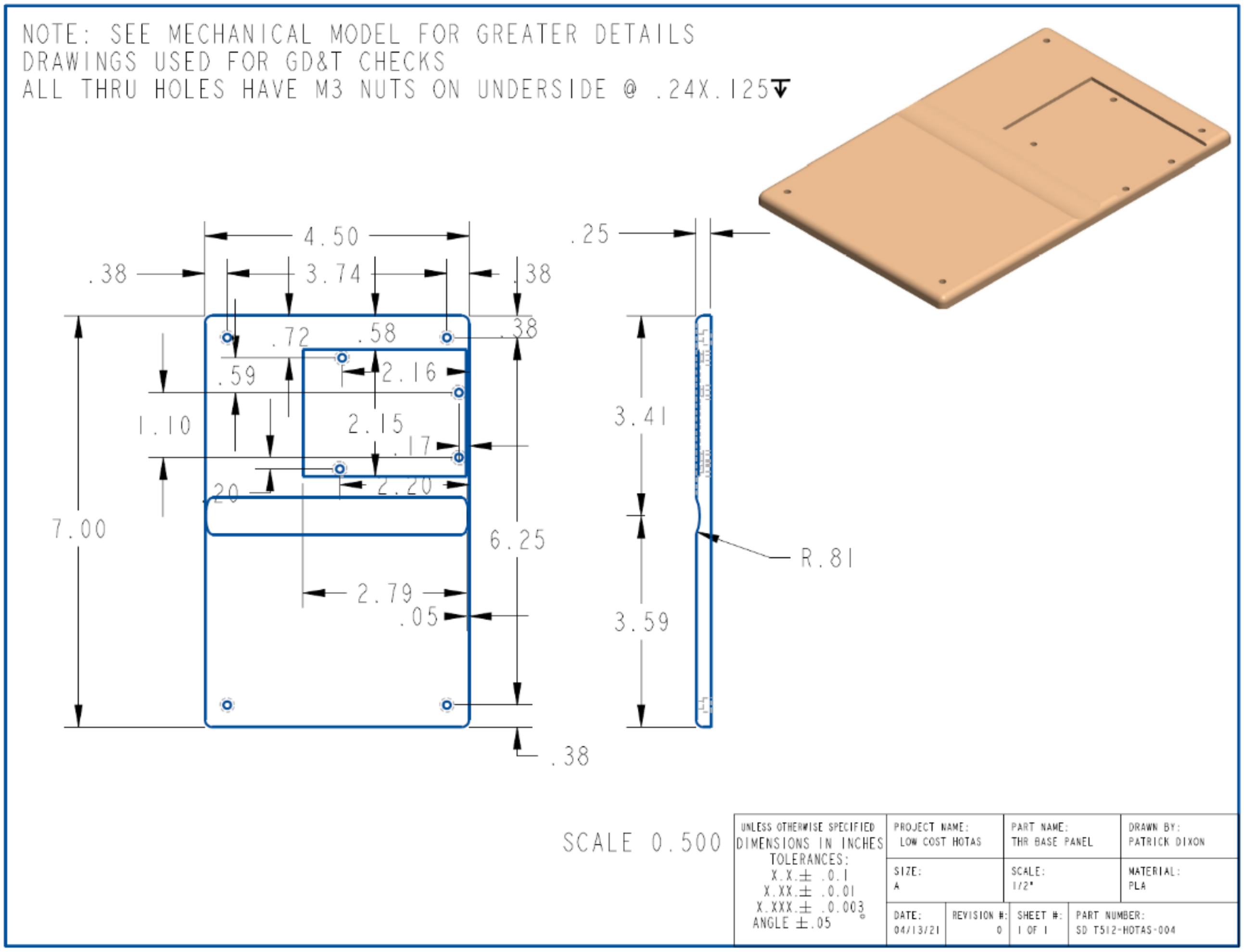

NOTE: SEE MECHANICAL MODEL FOR GREATER DETAILS
DRAWINGS USED FOR GD&T CHECKS
THIS PART IS CUT IN HALF THRU THE TWO SLOTS TO MAKE
TWO SEPARATE PARTS
GEAR SHOWN IS
KHK SSAY0.8-45/K8,
Module 0.8,
45 Tooth,
Hubless Gears with K-Clamps
.40
.60
.20
1.27
4.22
5.49
1.21
2.16
.75
.24
1.13
.24
.54
.29
.29
.17
R.27
R.37
65.0°
TWO SLOTS 180
DEGREES APART .25 WIDE
Ry.51
SCREW AND NUT HOLE ARE 0.24W
SCALE 0.750
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X.± .0.1
X.XX.± .0.01
X.XXX.± .0.003
ANGLE ±.05°
PROJECT NAME: LOW COST HOTAS
PART NAME: TH SHAFT&GEAR
DRAWN BY: PATRICK DIXON
SIZE: A
SCALE: 3/4"
MATERIAL: PLA
DATE: 04/13/21
REVISION #: 0
SHEET #: 1 OF 1
PART NUMBER: SD T512-HOTAS-009

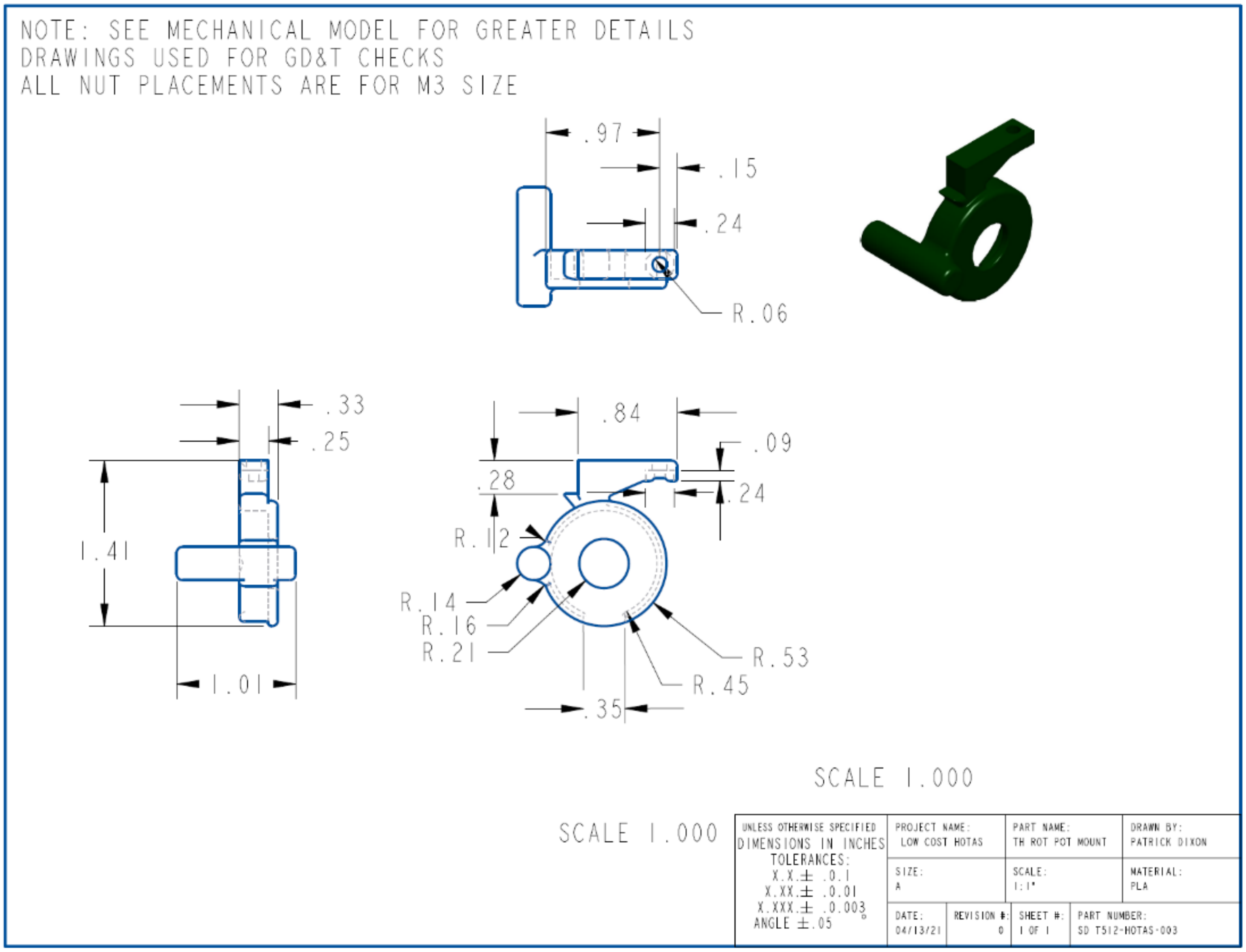
NOTE: SEE MECHANICAL MODEL FOR GREATER DETAILS
DRAWINGS USED FOR GD&T CHECKS
GEAR SHOWN IS A KHK SSAY0.8-28/K6,
Module 0.8, 28 Tooth, Hubless Gears with K-Clamps
THE CLAMPS HAVE BEEN REMOVED, A LARGER SHAFT HAS BEEN ADDED WITH A 1/4" HOLE PROVIDED TO SLIDE ONTO THE ROTARY POTENTIOMETER ↧0.5" AGAIN CHECK MODELS
DRAWING WAS UNABLE TO BE OBTAINED FROM KHK GEARS HOME WEBSITE.

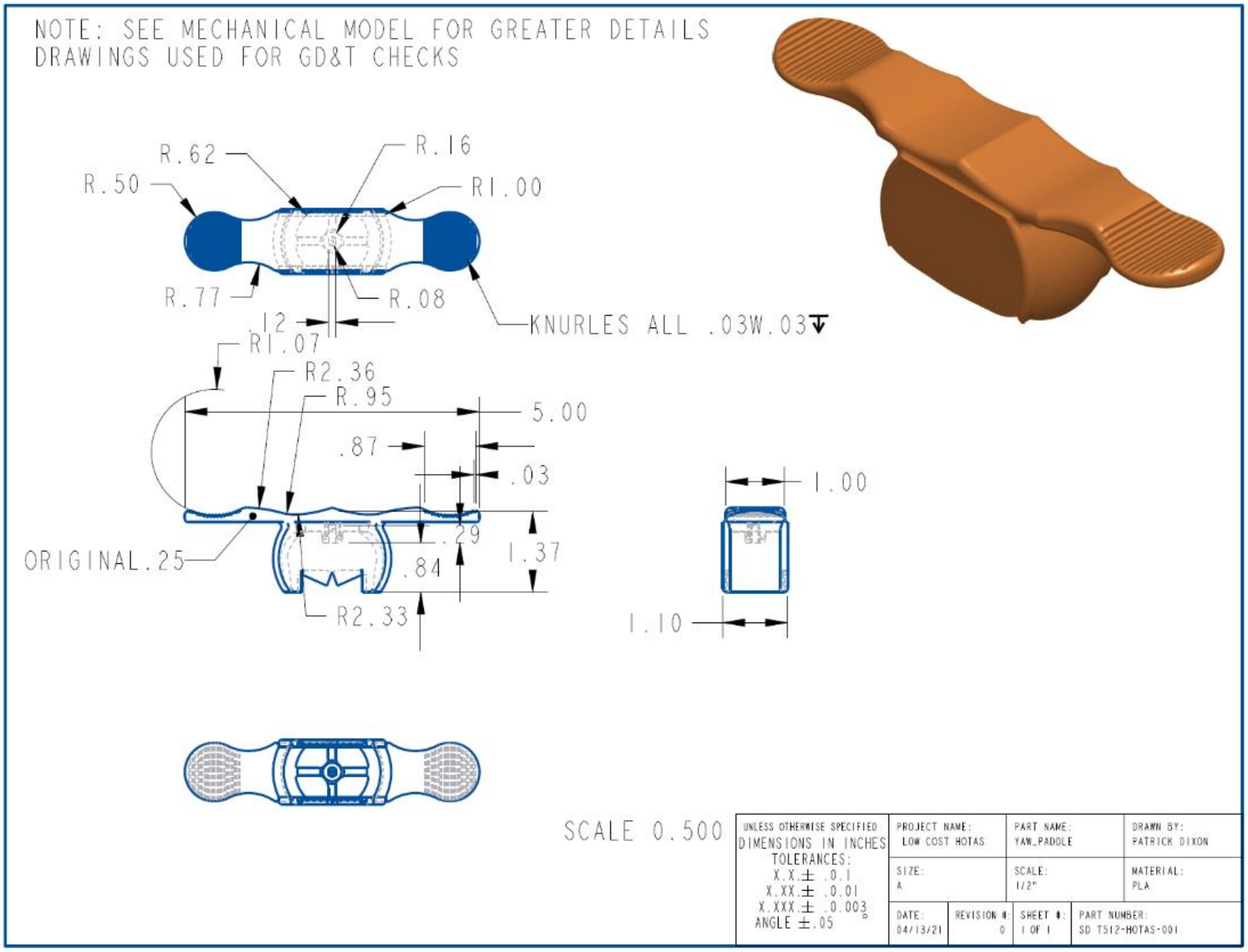


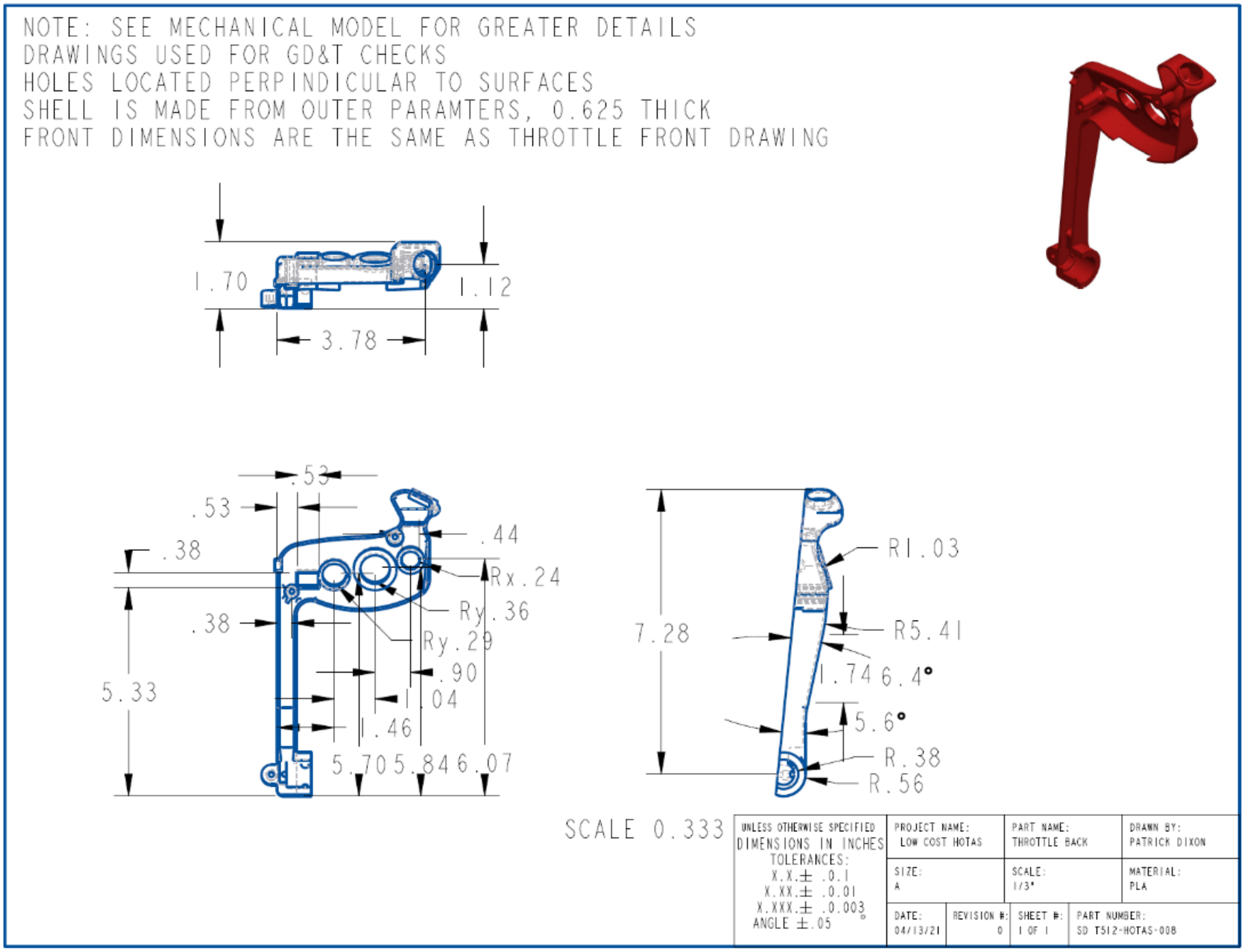
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES: X.X.± .0.1 X.XX.± .0.01 X.XXX.± .0.003 ANGLE ±.05 °	PROJECT NAME: LOW COST HOTAS		PART NAME: TH SMALL POT GEAR		DRAWN BY: PATRICK DIXON
	SIZE: A		SCALE: 2:1"		MATERIAL: PLA
	DATE: 04/13/21	REVISION #: 0	SHEET #: 1 OF 1	PART NUMBER: SD T512-HOTAS-010	

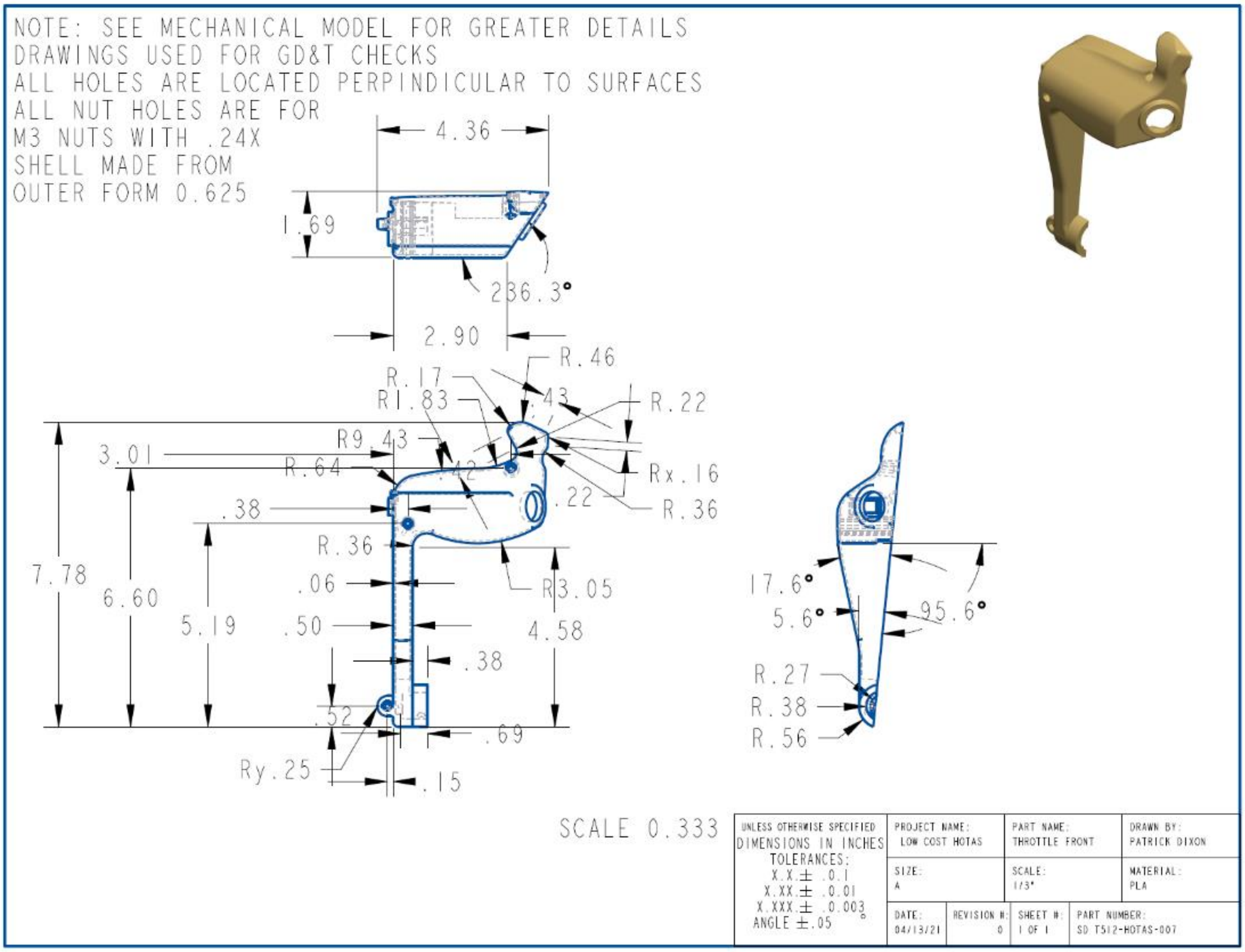

NOTE: SEE MECHANICAL MODEL FOR GREATER DETAILS
DRAWINGS USED FOR GD&T CHECKS
ALL CHAMFERS ARE 0.5
ALL ROUNDS UNLESS NOTED
R0.125
SCALE 0.333
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X ± .0.1
X.XX ± .0.01
X.XXX ± .0.003
ANGLE ± .05°
PROJECT NAME:
LOW COST HOTAS
PART NAME:
THROTTLE BASE
DRAWN BY:
PATRICK DIXON
SIZE:
A
SCALE:
1/3"
MATERIAL:
PLA
DATE:
04/13/21
REVISION #:
0
SHEET #:
1 OF 1
PART NUMBER:
SD T512-HOTAS-005

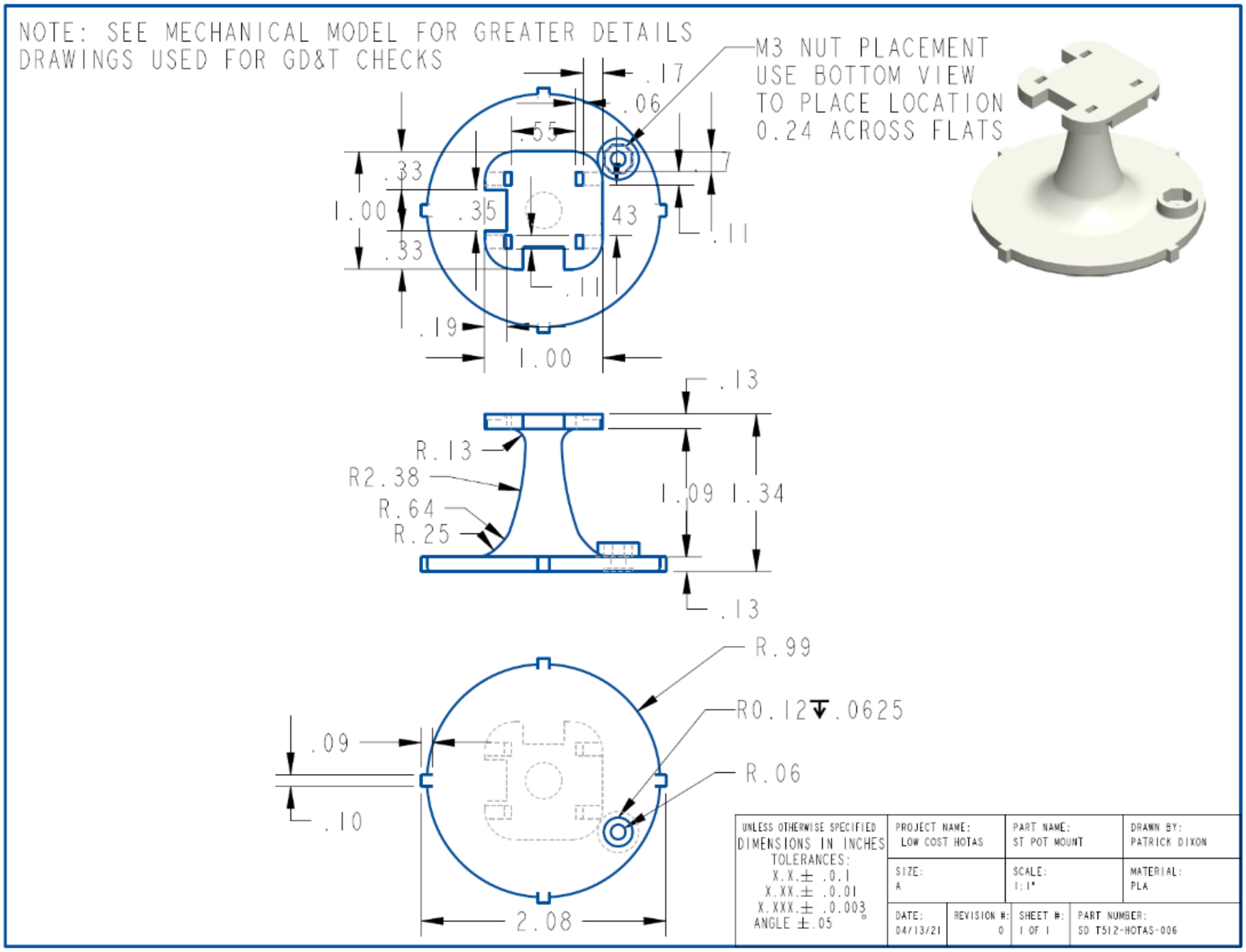

NOTE: SEE MECHANICAL MODEL FOR GREATER DETAILS
DRAWINGS USED FOR GD&T CHECKS
ALL THRU HOLES HAVE M3 NUTS ON UNDERSIDE @ .24X.125
R.81
SCALE 0.500
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X ± .0.1
X.XX ± .0.01
X.XXX ± .0.003
ANGLE ± .05°
PROJECT NAME: LOW COST HOTAS
PART NAME: THR BASE PANEL
DRAWN BY: PATRICK DIXON
SIZE: A
SCALE: 1/2"
MATERIAL: PLA
DATE: 04/13/21
REVISION #: 0
SHEET #: 1 OF 1
PART NUMBER: SD T512-HOTAS-004

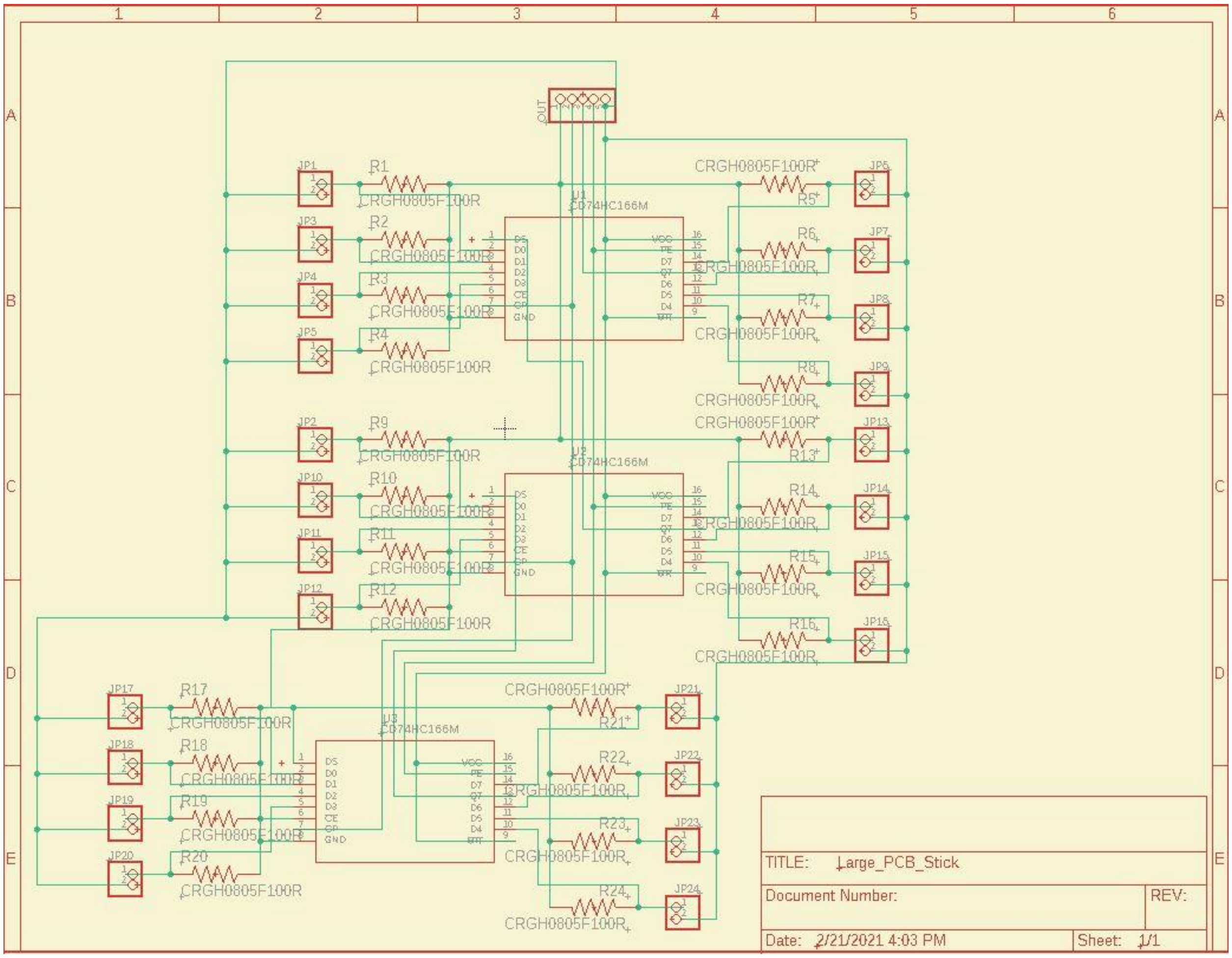

NOTE: SEE MECHANICAL MODEL FOR GREATER DETAILS
DRAWINGS USED FOR GD&T CHECKS
ALL NUT PLACEMENTS ARE FOR M3 SIZE
.97
.15
.24
R.06
.33
.25
1.41
1.01
.84
.09
.28
.24
R.12
R.14
R.16
R.21
R.53
R.45
.35
SCALE 1.000
SCALE 1.000
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X ± .0.1
X.XX ± .0.01
X.XXX ± .0.003
ANGLE ± .05°
PROJECT NAME: LOW COST HOTAS
PART NAME: TH ROT POT MOUNT
DRAWN BY: PATRICK DIXON
SIZE: A
SCALE: 1:1"
MATERIAL: PLA
DATE: 04/13/21
REVISION #: 0
SHEET #: 1 OF 1
PART NUMBER: SD T512-HOTAS-003


NOTE: SEE MECHANICAL MODEL FOR GREATER DETAILS
DRAWINGS USED FOR GD&T CHECKS
R.62
R.16
R.50
R1.00
R.77
R.08
.12
R1.07
KNURLES ALL .03W.03
R2.36
R.95
5.00
.87
.03
1.00
ORIGINAL.25
.29
1.37
.84
R2.33
1.10
SCALE 0.500
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X ± .0.1
X.XX ± .0.01
X.XXX ± .0.003
ANGLE ± .05°
PROJECT NAME: LOW COST HOTAS
PART NAME: YAW_PADDLE
DRAWN BY: PATRICK DIXON
SIZE: A
SCALE: 1/2"
MATERIAL: PLA
DATE: 04/13/21
REVISION #: 0
SHEET #: 1 OF 1
PART NUMBER: SD T512-HOTAS-001

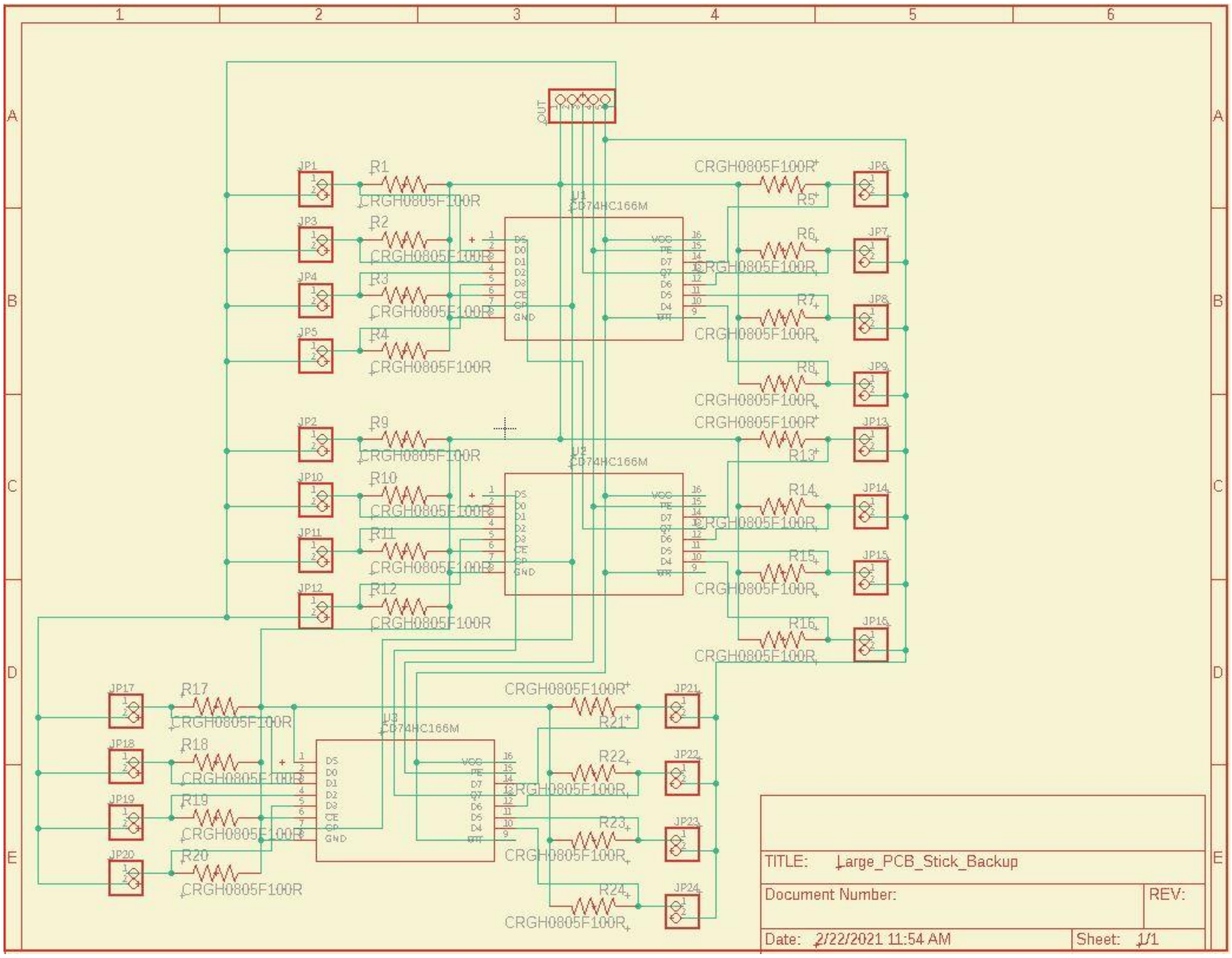

NOTE: SEE MECHANICAL MODEL FOR GREATER DETAILS
DRAWINGS USED FOR GD&T CHECKS
HOLES LOCATED PERPINDICULAR TO SURFACES
SHELL IS MADE FROM OUTER PARAMTERS, 0.625 THICK
FRONT DIMENSIONS ARE THE SAME AS THROTTLE FRONT DRAWING
1.70
1.12
3.78
.53
.53
.38
.44
Rx.24
Ry.36
.38
Ry.29
.90
5.33
1.04
1.46
5.70
5.84
6.07
7.28
R1.03
R5.41
1.74
6.4°
5.6°
R.38
R.56
SCALE 0.333
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X.± .0.1
X.XX.± .0.01
X.XXX.± .0.003
ANGLE ±.05°
PROJECT NAME: LOW COST HOTAS
PART NAME: THROTTLE BACK
DRAWN BY: PATRICK DIXON
SIZE: A
SCALE: 1/3"
MATERIAL: PLA
DATE: 04/13/21
REVISION #: 0
SHEET #: 1 OF 1
PART NUMBER: SD T512-HOTAS-008

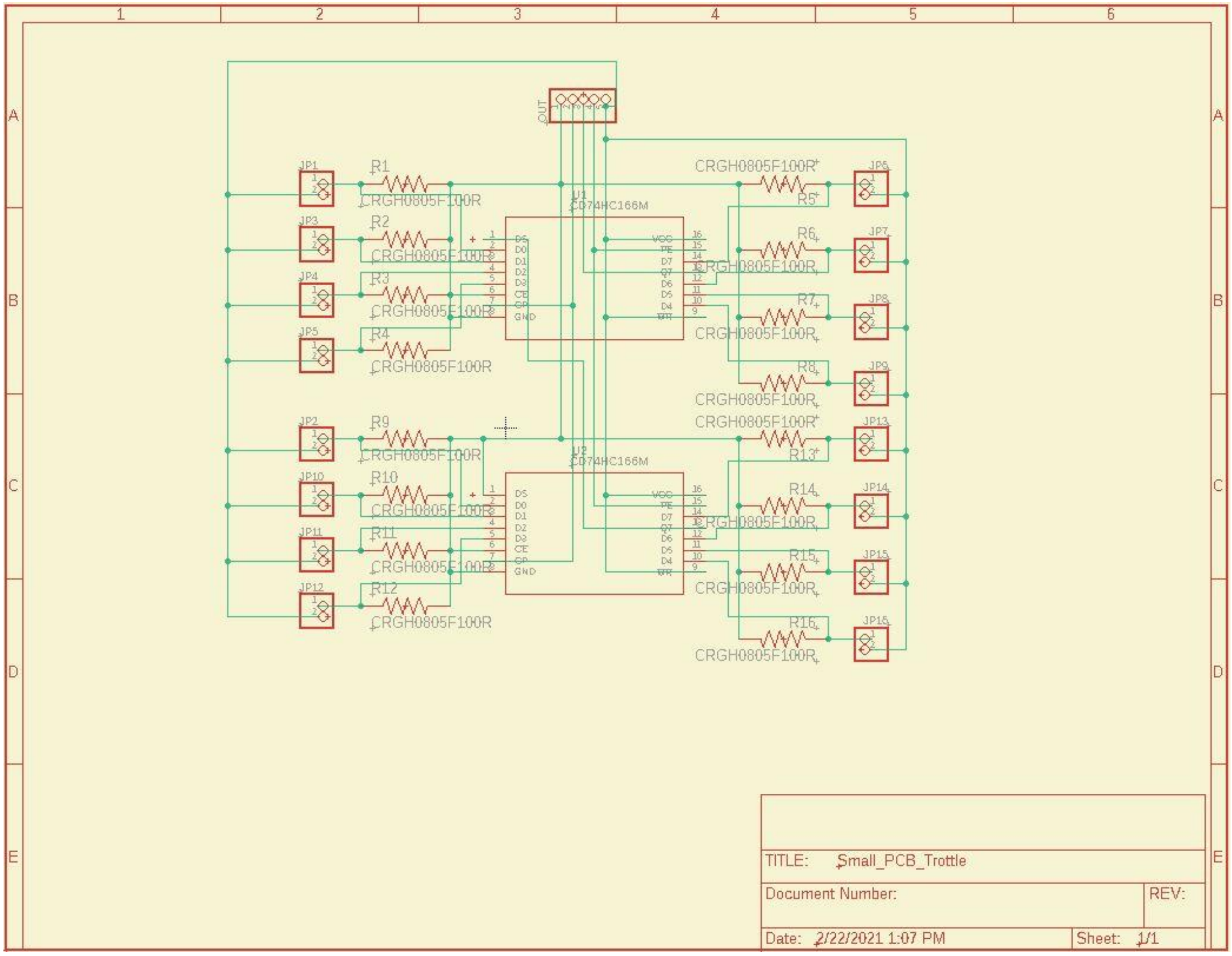

NOTE: SEE MECHANICAL MODEL FOR GREATER DETAILS
DRAWINGS USED FOR GD&T CHECKS
ALL HOLES ARE LOCATED PERPINDICULAR TO SURFACES
ALL NUT HOLES ARE FOR
M3 NUTS WITH .24X
SHELL MADE FROM
OUTER FORM 0.625
4.36
1.69
236.3°
2.90
R.46
R.17
R1.83
.43
R.22
R9.43
3.01
R.64
.42
Rx.16
.22
R.36
.38
R.36
7.78
6.60
5.19
.06
.50
R3.05
4.58
.38
.52
.69
Ry.25
.15
17.6°
5.6°
95.6°
R.27
R.38
R.56
SCALE 0.333
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X ± .0.1
X.XX ± .0.01
X.XXX ± .0.003
ANGLE ± .05°
PROJECT NAME: LOW COST HOTAS
PART NAME: THROTTLE FRONT
DRAWN BY: PATRICK DIXON
SIZE: A
SCALE: 1/3"
MATERIAL: PLA
DATE: 04/13/21
REVISION #: 0
SHEET #: 1 OF 1
PART NUMBER: SD T512-HOTAS-007


NOTE: SEE MECHANICAL MODEL FOR GREATER DETAILS
DRAWINGS USED FOR GD&T CHECKS
M3 NUT PLACEMENT
USE BOTTOM VIEW
TO PLACE LOCATION
0.24 ACROSS FLATS
.17
.06
.55
.33
1.00
.35
.43
.33
.11
.11
.19
1.00
.13
R.13
R2.38
R.64
R.25
1.09
1.34
.13
R.99
R0.12 ↧.0625
.09
R.06
.10
2.08
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X.± .0.1
X.XX.± .0.01
X.XXX.± .0.003
ANGLE ±.05°
PROJECT NAME:
LOW COST HOTAS
PART NAME:
ST POT MOUNT
DRAWN BY:
PATRICK DIXON
SIZE:
A
SCALE:
1:1*
MATERIAL:
PLA
DATE:
04/13/21
REVISION #:
0
SHEET #:
1 OF 1
PART NUMBER:
SD T512-HOTAS-006



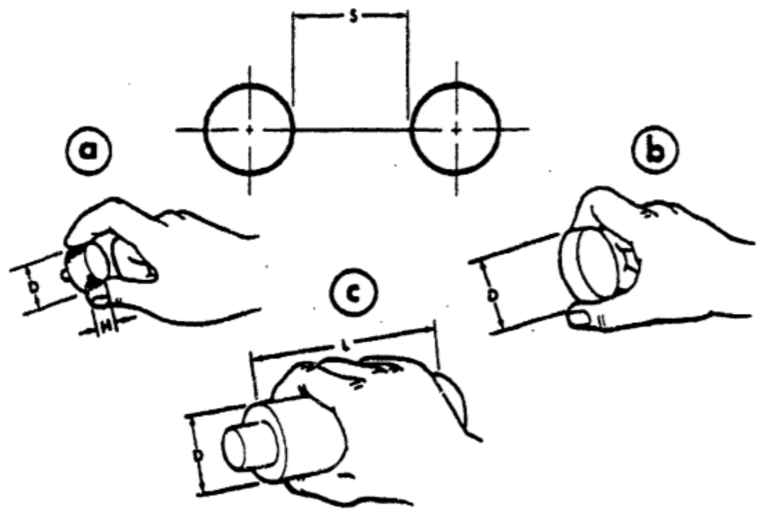
TITLE: Large_PCB_Stick
Document Number:
REV:
Date: 2/21/2021 4:03 PM
Sheet: 1/1


TITLE: Large_PCB_Stick_Backup
Document Number:
REV:
Date: 2/22/2021 11:54 AM
Sheet: 1/1



MIL standard 1472 References

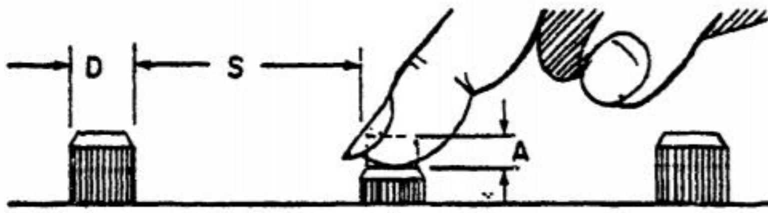
Mil Standard 1472 document parts relevant currently (note mil standard 1472 doc is over 400 pages)



	DIMENSIONS				
	(a) Fingertip Grasp		(b) Thumb and Finger Encircled	(c) Palm Grasp	
	H Height	D Diameter	D Diameter	D Diameter	L Length
Minimum	13 mm (1/2 in.)	10 mm (3/8 in.)	25 mm (1 in.)	38 mm (1-1/2 in.)	75 mm (3 in.)
Maximum	25 mm (1 in.)	100 mm (4 in.)	75 mm (3 in.)	75 mm (3 in.)	-
	TORQUE		SEPARATION		
	*	**	S One Hand Individually	S Two Hands Simultaneously	
Minimum	-		25 mm (1 in.)	50 mm (2 in.)	
Optimum	-	-	50 mm (2 in.)	125 mm (5 in.)	
Maximum	32 mN-m (4-1/2 in.-oz.)	42 mN-m (6 in.-oz.)	-	-	

*To and including 25 mm (1.0 in.) diameter knobs
**Greater than 25 mm (1.0 in.) diameter knobs

FIGURE 7. KNOBS



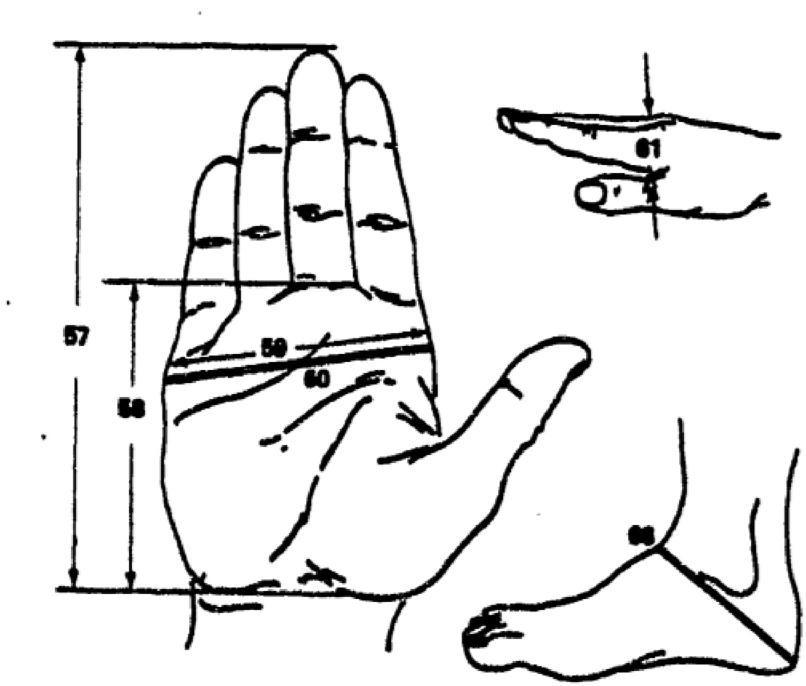
	DIMENSIONS DIAMETER D		RESISTANCE		
	Fingertip	Thumb or Palm	Single Finger	Different Fingers	Thumb or Palm
Minimum	9.5 mm (3/8 in.)	19 mm (3/4 in.)	2.8 N (10 oz.)	1.4 N (5 oz.)	2.8 N (10 oz.)
Maximum	25 mm (1 in.)		11 N (40 oz.)	5.6 N (20 oz.)	23 N (80 oz.)

	DISPLACEMENT A	
	Fingertip	Thumb or Palm
Minimum	2 mm (5/64 in.)	3 mm (1/8 in.)
Maximum	6 mm (1/4 in.)	38 mm (1-1/2 in.)

	SEPARATION S			
	Single Finger	Single Finger Sequential	Different Fingers	Thumb or Palm
Minimum	13 mm (1/2 in.)	6 mm (1/4 in.)	6 mm (1/4 in.)	25 mm (1 in.)
Preferred	50 mm (2 in.)	13 mm (1/2 in.)	13 mm (1/2 in.)	150 mm (6 in.)

Note: Above data for barehand application. For gloved hand operation, minima should be suitably adjusted.

FIGURE 11. PUSHBUTTONS (FINGER OR HAND OPERATED)


57
58
59
60
61

	PERCENTILE VALUES IN CENTIMETERS					
	5th PERCENTILE			95th PERCENTILE		
	GROUND TROOPS	AVIATORS	WOMEN	GROUND TROOPS	AVIATORS	WOMEN
HAND DIMENSIONS						
57 HAND LENGTH	17.4	17.7	16.1	20.7	20.7	20.0
58 PALM LENGTH	9.6	10.0	9.0	11.7	11.9	10.8
59 HAND BREADTH	8.1	8.2	6.9	9.7	9.7	8.5
60 HAND CIRCUMFERENCE	19.5	19.6	16.8	23.6	23.1	19.9
61 HAND THICKNESS		2.4			3.5	
FOOT DIMENSIONS						
62 FOOT LENGTH	24.5	24.4	22.2	29.0	29.0	26.5
63 INSTEP LENGTH	17.7	17.5	16.3	21.7	21.4	19.6
64 FOOT BREADTH	9.0	9.0	8.0	10.9	11.6	9.8
65 FOOT CIRCUMFERENCE	22.5	22.6	20.8	27.4	27.0	24.5
66 HEEL–ANKLE CIRCUMFERENCE	31.3	30.7	28.5	37.0	36.3	33.3
	PERCENTILE VALUES IN INCHES					
HAND DIMENSIONS						
57 HAND LENGTH	6.85	6.98	6.32	8.13	8.14	7.89
58 PALM LENGTH	3.77	3.92	3.56	4.61	4.69	4.24
59 HAND BREADTH	3.20	3.22	2.72	3.83	3.80	3.33
60 HAND CIRCUMFERENCE	7.68	7.71	6.62	9.28	9.11	7.82
61 HAND THICKNESS		0.96			1.37	
FOOT DIMENSIONS						
62 FOOT LENGTH	9.65	9.62	8.74	11.41	11.42	10.42
63 INSTEP LENGTH	6.97	6.88	6.41	8.54	8.42	7.70
64 FOOT BREADTH	3.53	3.54	3.16	4.29	4.58	3.84
65 FOOT CIRCUMFERENCE	8.86	8.91	8.17	10.79	10.62	9.65
66 HEEL–ANGLE CIRCUMFERENCE	12.32	12.08	11.21	14.57	14.30	13.11

References

McConomy, S. *180910 Scope Customer Requirements* [PDF document]. Retrieved from Lecture Notes Online Website: https://famu-fsu-eng.instructure.com/courses/114/files/4363?module_item_id=1743

McConomy, S. *181017 – Concept Selection* [PDF document]. Retrieved from Lecture Notes Online Website: https://famu-fsu-eng.instructure.com/courses/114/files/9521?module_item_id=2704

FAMU-FSU College of Engineering
Project Hazard Assessment Policy and Procedures

INTRODUCTION

University laboratories are not without safety hazards. Those circumstances or conditions that might go wrong must be predicted and reasonable control methods must be determined to prevent incident and injury. The FAMU-FSU College of Engineering is committed to achieving and maintaining safety in all levels of work activities.

PROJECT HAZARD ASSESSMENT POLICY

Principal investigator (PI)/instructor are responsible and accountable for safety in the research and teaching laboratory. Prior to starting an experiment, laboratory workers must conduct a project hazard assessment (PHA) to identify health, environmental and property hazards and the proper control methods to eliminate, reduce or control those hazards. PI/instructor must review, approve, and sign the written PHA and provide the identified hazard control measures. PI/instructor continually monitor projects to ensure proper controls and safety measures are available, implemented, and followed. PI/instructor are required to reevaluate a project anytime there is a change in scope or scale of a project and at least annually after the initial review.

PROJECT HAZARD ASSESSMENT PROCEDURES

It is FAMU-FSU College of Engineering policy to implement followings:

1. Laboratory workers (i.e. graduate students, undergraduate students, postdoctoral, volunteers, etc.) performing a research in FAMU-FSU College of Engineering are required to conduct PHA prior to commencement of an experiment or any project change in order to identify existing or potential hazards and to determine proper measures to control those hazards.
2. PI/instructor must review, approve and sign the written PHA.
3. PI/instructor must ensure all the control methods identified in PHA are available and implemented in the laboratory.
4. In the event laboratory personnel are not following the safety precautions, PI/instructor must take firm actions (e.g. stop the work, set a meeting to discuss potential hazards and consequences, ask personnel to review the safety rules, etc.) to clarify the safety expectations.
5. PI/instructor must document all the incidents/accidents happened in the laboratory along with the PHA document to ensure that PHA is reviewed/modified to prevent reoccurrence. In the event of PHA modification a revision number should be given to the PHA, so project members know the latest PHA revision they should follow.
6. PI/instructor must ensure that those findings in PHA are communicated with other students working in the same laboratory (affected users).
7. PI/instructor must ensure that approved methods and precautions are being followed by :
    a. Performing periodic laboratory visits to prevent the development of unsafe practice.
    b. Quick reviewing of the safety rules and precautions in the laboratory members meetings.
    c. Assigning a safety representative to assist in implementing the expectations.
    d. Etc.

8. A copy of this PHA must be kept in a binder inside the laboratory or PI/instructor's office (if experiment steps are confidential).

Project Hazard Assessment Worksheet				
PI/instructor: Dr. McConomy	Phone #: 850-410-6624	Dept.: ME	Start Date: January 2021	Revision number: 1
Project: Senior Design: Low Cost HOTAS Team 512			Location(s): ME Senior Design Lab	
Team member(s): Robert Blount, Connor Chuppe, Robert Craig, Patrick Dixon			Phone #: 5613063836	Email: cnc17e@my.fsu.edu

Experiment Steps	**Location**	**Person assigned**	**Identify hazards or potential failure points**	**Control method**	**PPE**	**List proper method of hazardous waste disposal, if any.**	**Residual Risk**	**Specific rules based on the residual risk**
Soldering (Wiring)	ME Senior Design Lab	Entire Team	Burning of skin Electrocution Fire Contaminated Air Lacerations	Ventilated Room	Gloves Safety Goggles	Place in container labeled "Lead Solder Waste for Recycling"	HAZARD: 2 CONSEQ:C Residual: 2	Shown below
3D Printing	ME Senior Design Lab	Entire Team	Contaminated Air Burning of Skin	Use a filament that is not harmful Place in enclosure	Respiratory Mask	N/A	HAZARD: 1 CONSEQ:A Residual:2	Shown below
Heat Shrinking	ME Senior Design Lab	Entire Team	Burning of Skin	Ventilated Room	Gloves Safety Goggles	N/A	HAZARD: 2 CONSEQ:A Residual:3	Shown below
Mounting Components Together	ME Senior Design Lab	Entire Team	Contaminated Air, Lacerations, pinches	Ventilated Room	Gloves Respiratory Mask	N/A	HAZARD: 1 CONSEQ:A Residual:1	Shown below
Maneuvering in Senior	ME Senior	Entire Team	Trip and Fall, Struck by projectile	Clean floor Organized room	Closed-toed shoes Long pants	N/A	HAZARD: 1 CONSEQ:A,B,C	Shown below

Design Lab (physical-ergonomic hazards)	Design Lab						Residual:2	
Biological hazard (Covid-19)	ME Senior Design Lab	Entire Team	Covid-19, other types of infectious diseases	Masks, social distancing, clean surfaces often, test semi regularly	Masks, face shields, sanitization products	Discard of masks in appropriate containers	HAZARD: 3 CONSEQ: B, C,D,E Residual: varies 1-5	Will discuss with instructor-lab supervisor
Hazardous substances (epoxy, glue)	ME Senior Design Lab	Entire Team	Having skin exposure to epoxy or fast setting glue(burns, skin removal)	Using PPE, or advisory guidance	Gloves, all standard lab clothing	If residual material, left to harden in a designated container before disposal into trash.	HAZARD: 3 CONSEQ: B,C Residual: 2	Shown below

Principal investigator(s)/ instructor PHA: I have reviewed and approved the PHA worksheet.

Name	Signature	Date	Name	Signature	Date
________________________	______________	________	________________________	______________	________

Team members: I certify that I have reviewed the PHA worksheet, am aware of the hazards, and will ensure the control measures are followed.

Name	Signature	Date	Name	Signature	Date
Robert Blount		12/03/2020	Robert Craig		12/03/2020
Connor Chuppe		12/03/2020	Patrick Dixon		12/03/2020

ed.

DEFINITIONS:

Hazard: Any situation, object, or behavior that exists, or that can potentially cause ill health, injury, loss or property damage e.g. electricity, chemicals, biohazard materials, sharp objects, noise, wet floor, etc. OSHA defines hazards as "*any source of potential damage, harm or adverse health effects on something or someone*". A list of hazard types and examples are provided in appendix A.

Hazard control: Hazard control refers to workplace measures to eliminate/minimize adverse health effects, injury, loss, and property damage. Hazard control practices are often categorized into following three groups (priority as listed):

1. **Engineering control:** physical modifications to a process, equipment, or installation of a barrier into a system to minimize worker exposure to a hazard. Examples are ventilation (fume hood, biological safety cabinet), containment (glove box, sealed containers, barriers), substitution/elimination

(consider less hazardous alternative materials), process controls (safety valves, gauges, temperature sensor, regulators, alarms, monitors, electrical grounding and bonding), etc.

2. **Administrative control:** changes in work procedures to reduce exposure and mitigate hazards. Examples are reducing scale of process (micro-scale experiments), reducing time of personal exposure to process, providing training on proper techniques, writing safety policies, supervision, requesting experts to perform the task, etc.

3. **Personal protective equipment (PPE):** equipment worn to minimize exposure to hazards. Examples are gloves, safety glasses, goggles, steel toe shoes, earplugs or muffs, hard hats, respirators, vests, full body suits, laboratory coats, etc.

Team member(s): Everyone who works on the project (i.e. grads, undergrads, postdocs, etc.). The primary contact must be listed first and provide phone number and email for contact.

Safety representative: Each laboratory is encouraged to have a safety representative, preferably a graduate student, in order to facilitate the implementation of the safety expectations in the laboratory. Duties include (but are not limited to):

- Act as a point of contact between the laboratory members and the college safety committee members.
- Ensure laboratory members are following the safety rules.
- Conduct periodic safety inspection of the laboratory.
- Schedule laboratory clean up dates with the laboratory members.
- Request for hazardous waste pick up.

Residual risk: Residual Risk Assessment Matrix are used to determine project's risk level. The hazard assessment matrix (table 1) and the residual risk assessment matrix (table2) are used to identify the residual risk category.

The instructions to use hazard assessment matrix (table 1) are listed below:

1. Define the workers familiarity level to perform the task and the complexity of the task.
2. Find the value associated with familiarity/complexity (1 – 5) and enter value next to: HAZARD on the PHA worksheet.

Table 1. Hazard assessment matrix.

		Complexity		
		Simple	Moderate	Difficult
Familiarity Level	Very Familiar	1	2	3
	Somewhat Familiar	2	3	4
	Unfamiliar	3	4	5

The instructions to use residual risk assessment matrix (table 2) are listed below:

1. Identify the row associated with the familiarity/complexity value (1 – 5).
2. Identify the consequences and enter value next to: CONSEQ on the PHA worksheet. Consequences are determined by defining what would happen in a worst case scenario if controls fail.
   a. Negligible: minor injury resulting in basic first aid treatment that can be provided on site.
   b. Minor: minor injury resulting in advanced first aid treatment administered by a physician.
   c. Moderate: injuries that require treatment above first aid but do not require hospitalization.
   d. Significant: severe injuries requiring hospitalization.
   e. Severe: death or permanent disability.
3. Find the residual risk value associated with assessed hazard/consequences: Low –Low Med – Med– Med High – High.
4. Enter value next to: RESIDUAL on the PHA worksheet.

Table 2. Residual risk assessment matrix.

Assessed Hazard Level	**Consequences**

	Negligible	Minor	Moderate	Significant	Severe
5	Low Med	Medium	Med High	High	High
4	Low	Low Med	Medium	Med High	High
3	Low	Low Med	Medium	Med High	Med High
2	Low	Low Med	Low Med	Medium	Medium
1	Low	Low	Low Med	Low Med	Medium

Specific rules for each category of the residual risk:

Low:

- Safety controls are planned by both the worker and supervisor.
- Proceed with supervisor authorization.

Low Med:

- Safety controls are planned by both the worker and supervisor.
- A second worker must be in place before work can proceed (buddy system).
- Proceed with supervisor authorization.

Med:

- After approval by the PI, a copy must be sent to the Safety Committee.
- A written Project Hazard Control is required and must be approved by the PI before proceeding. A copy must be sent to the Safety Committee.
- A second worker must be in place before work can proceed (buddy system).
- Limit the number of authorized workers in the hazard area.

Med High:

- After approval by the PI, the Safety Committee and/or EHS must review and approve the completed PHA.
- A written Project Hazard Control is required and must be approved by the PI and the Safety Committee before proceeding.
- Two qualified workers must be in place before work can proceed.
- Limit the number of authorized workers in the hazard area.

High:

- The activity will not be performed. The activity must be redesigned to fall in a lower hazard category.

Appendix A: Hazard types and examples

Types of Hazard	**Example**
Physical hazards	Wet floors, loose electrical cables objects protruding in walkways or doorways
Ergonomic hazards	Lifting heavy objects Stretching the body Twisting the body Poor desk seating
Psychological hazards	Heights, loud sounds, tunnels, bright lights
Environmental hazards	Room temperature, ventilation contaminated air, photocopiers, some office plants acids
Hazardous substances	Alkalis solvents
Biological hazards	Hepatitis B, new strain influenza

Radiation hazards	Electric welding flashes Sunburn
Chemical hazards	Effects on central nervous system, lungs, digestive system, circulatory system, skin, reproductive system. Short term (acute) effects such as burns, rashes, irritation, feeling unwell, coma and death. Long term (chronic) effects such as mutagenic (affects cell structure), carcinogenic (cancer), teratogenic (reproductive effect), dermatitis of the skin, and occupational asthma and lung damage.
Noise	High levels of industrial noise will cause irritation in the short term, and industrial deafness in the long term.
Temperature	Personal comfort is best between temperatures of 16°C and 30°C, better between 21°C and 26°C. Working outside these temperature ranges: may lead to becoming chilled, even hypothermia (deep body cooling) in the colder temperatures, and may lead to dehydration, cramps, heat exhaustion, and hyperthermia (heat stroke) in the warmer temperatures.
Being struck by	This hazard could be a projectile, moving object or material. The health effect could be lacerations, bruising, breaks, eye injuries, and possibly death.
Crushed by	A typical example of this hazard is tractor rollover. Death is usually the result
Entangled by	Becoming entangled in machinery. Effects could be crushing, lacerations, bruising, breaks amputation and death.
High energy sources	Explosions, high pressure gases, liquids and dusts, fires, electricity and sources such as lasers can all have serious effects on the body, even death.
Vibration	Vibration can affect the human body in the hand arm with `white-finger' or Raynaud's Syndrome, and the whole body with motion sickness, giddiness, damage to bones and audits, blood pressure and nervous system problems.
Slips, trips and falls	A very common workplace hazard from tripping on floors, falling off structures or down stairs, and slipping on spills.
Radiation	Radiation can have serious health effects. Skin cancer, other cancers, sterility, birth deformities, blood changes, skin burns and eye damage are examples.
Physical	Excessive effort, poor posture and repetition can all lead to muscular pain, tendon damage and deterioration to bones and related structures
Psychological	Stress, anxiety, tiredness, poor concentration, headaches, back pain and heart disease can be the health effects
Biological	More common in the health, food and agricultural industries. Effects such as infectious disease, rashes and allergic response.

Project Hazard Control- For Projects with Medium and Higher Risks

Name of Project: Low-Cost Hands-on Throttle and Stick		Date of submission: 12/3/20
Team member	**Phone number**	**e-mail**
Robert Blount	850-206-6022	Robert1.blount@famu.edu
Connor Chuppe	561-306-3836	Cnc17e@my.fsu.edu
Robert Craig	850-728-7039	robert2.craig@famu.edu
Patrick Dixon	850-218-8996	Pdd17@my.fsu.edu
Faculty mentor	**Phone number**	**e-mail**
Shayne McConomy	850-410-6624	smcconomy@eng.famu.fsu.edu
Rewrite the project steps to include all safety measures taken for each step or combination of steps. Be specific (don't just state "be careful").		
3D Printing: Don't touch components that reach high temperatures, when cleaning part post print examine part for sharp edges first, wear gloves. Soldering (Wiring): Wear gloves and safety goggles, hold hand that is not holding the soldering iron far enough away to avoid burns, don't touch the hot part of the soldering iron. Heat Shrinking: Wear gloves, when using heat gun keep hand holding the heat shrink far away from hot air. Mounting Components Together: Don't breathe in epoxy, when screwing parts together be mindful of hand placement, don't force things together if they aren't fitting. Maneuvering in Senior Design Lab: Have situational awareness as too what other teams are working in the lab, don't rush or run in the lab. Covid 19: Wear a mask and social distance at all times, sanitize workstations before and after working, clean hands before and after entering the lab, don't come to lab if you have had known contact with someone Covid 19 positive.		
Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.		
In looking at an accident that occurred in October of 2010 where an 18-year-old male burnt his middle finger on a soldering iron, the emergency response for this, if it were to happen to us, would be to cool the burn, apply lotion and bandage the wound, notify another student working in the lab. If a severe burn, drive to the hospital and notify an employee of the college, if extremely severe call 911/Emergency responders. Common accidents that have occurred with 3D printing are minor burns in which the emergency response would be the same as stated above. Lacerations of the skin from people cleaning their part post print. If the cut is minor, clean the cut and bandage the wound, notify a fellow student in the lab. If severe, notify an employee of the college and		

determine if it needs to be stitched. If stiches are needed either drive to the hospital or dial 911 for emergency responders if cut is extreme.

For the potential risks associated with the heat shrink usage and mounting components together, the same procedure will be followed as stated above for either a cut or a burn.

List emergency response contact information:

- Call 911 for injuries, fires or other emergency situations
- Call your department representative to report a facility concern

Name	Phone number	Faculty or other COE emergency contact	Phone number
Keith Larson	**(850)-410-6108**	**Larson@eng.famu.fsu.edu**	
Patrick Hollis	**(850)-410-6319**	**Hollis@eng.famu.fsu.edu**	

Safety review signatures

Team member	Date	Faculty mentor	Date
Robert Blount	**12/3/20**		
Connor Chuppe	**12/3/20**		
Patrick Dixon	**12/3/20**		
Robert Craig	**12/3/20**		

Report all accidents and near misses to the faculty mentor.

Name of Project: Low-Cost Hands-on Throttle and Stick		Date of submission: 12/3/20
Team member	**Phone number**	**e-mail**
Robert Blount	**850-206-6022**	**Robert1.blount@famu.edu**
Connor Chuppe	**561-306-3836**	**Cnc17e@my.fsu.edu**
Robert Craig	**850-728-7039**	**robert2.craig@famu.edu**
Patrick Dixon	**850-218-8996**	**Pdd17@my.fsu.edu**
Faculty mentor	**Phone number**	**e-mail**
Shayne McConomy	**850-410-6624**	**smcconomy@eng.famu.fsu.edu**

Rewrite the project steps to include all safety measures taken for each step or combination of steps. Be specific (don't just state "be careful").

3D Printing: Don't touch components that reach high temperatures, when cleaning part post print examine part for sharp edges first, wear gloves.

Soldering (Wiring): Wear gloves and safety goggles, hold hand that is not holding the soldering iron far enough away to avoid burns, don't touch the hot part of the soldering iron.

Heat Shrinking: Wear gloves, when using heat gun keep hand holding the heat shrink far away from hot air.

Mounting Components Together: Don't breathe in epoxy, when screwing parts together be mindful of hand placement, don't force things together if they aren't fitting.

Maneuvering in Senior Design Lab: Have situational awareness as too what other teams are working in the lab, don't rush or run in the lab.

Covid 19: Wear a mask and social distance at all times, sanitize workstations before and after working, clean hands before and after entering the lab, don't come to lab if you have had known contact with someone Covid 19 positive.

Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.

In looking at an accident that occurred in October of 2010 where an 18-year-old male burnt his middle finger on a soldering iron, the emergency response for this, if it were to happen to us, would be to cool the burn, apply lotion and bandage the wound, notify another student working in the lab. If a severe burn, drive to the hospital and notify an employee of the college, if extremely severe call 911/Emergency responders.

Common accidents that have occurred with 3D printing are minor burns in which the emergency response would be the same as stated above. Lacerations of the skin from people cleaning their part post print. If the cut is minor, clean the cut and bandage the wound, notify a fellow student in the lab. If severe, notify an employee of the college and

determine if it needs to be stitched. If stiches are needed either drive to the hospital or dial 911 for emergency responders if cut is extreme.

For the potential risks associated with the heat shrink usage and mounting components together, the same procedure will be followed as stated above for either a cut or a burn.

List emergency response contact information:

- Call 911 for injuries, fires or other emergency situations
- Call your department representative to report a facility concern

Name	Phone number	Faculty or other COE emergency contact	Phone number
Keith Larson	**(850)-410-6108**	**Larson@eng.famu.fsu.edu**	
Patrick Hollis	**(850)-410-6319**	**Hollis@eng.famu.fsu.edu**	

Safety review signatures

Team member	Date	Faculty mentor	Date
Robert Blount	**12/3/20**		
Connor Chuppe	**12/3/20**		
Patrick Dixon	**12/3/20**		
Robert Craig	**12/3/20**		