Lockheed Martin Low-Cost F-35 Simulator

Senior Design Team 514

Francisco Lopez

Meet the Team

Jonah Gibbons
Electrical & Manufacturing Engineer

Laiken Kinsey
Test Engineer & Project Manager

Francisco Lopez
Mechanical & Product Design Engineer

Branden Pacer
Mechanical Engineer & Gimbal Designer

Will Rickles
Mechatronics Engineer

Emelia Rodriguez
Research Engineer

Francisco Lopez

Sponsor and Advisor

LOCKHEED MARTIN

Andrew Filiault

Mechanical Engineer, B.S.

JSF F-35 Pilot Training and Training Infrastructure Systems

FAMU-FSU College of Engineering

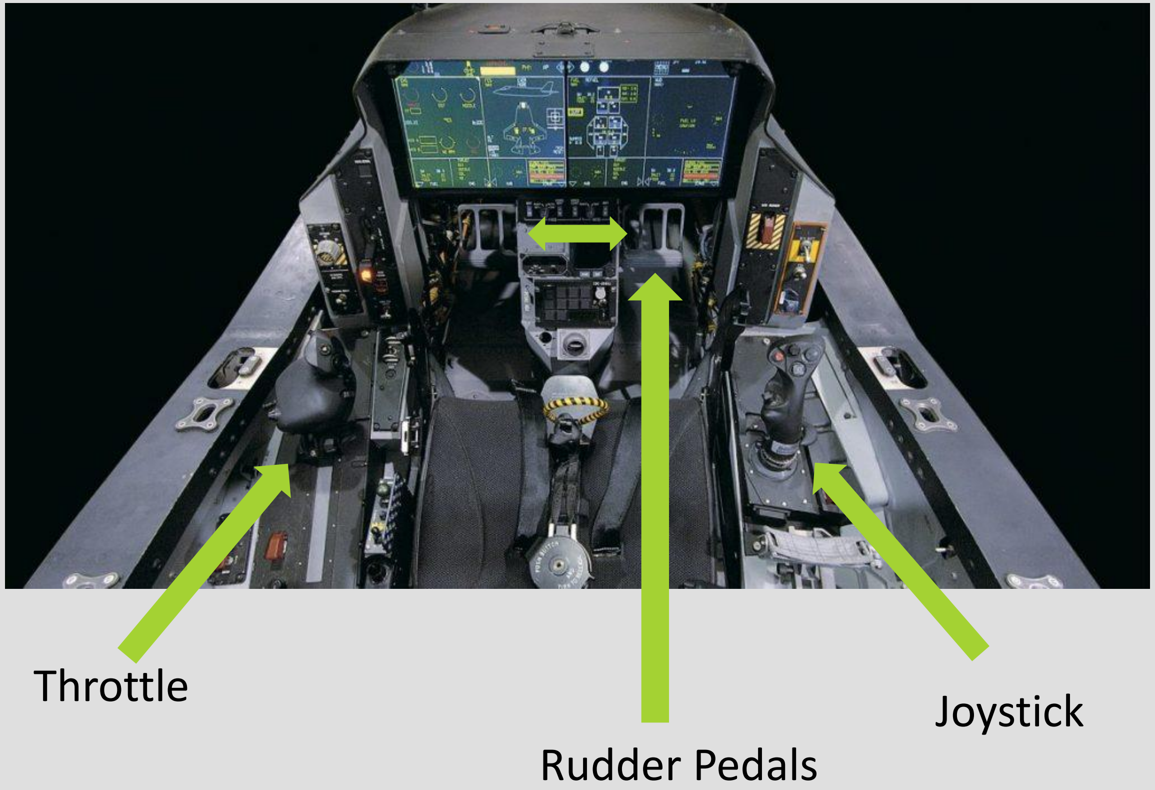
Brandon Krick

Mechanical Engineer, Ph.D.

Associate Professor

Francisco Lopez

Project Objective



The objective of this project is to create low-cost F-35 flight controls that integrate with Lockheed Martin's simulator software to be used in the pilot training program

Francisco Lopez

3D Printed Cockpit and Desktop Simulator

- Pilots train in simulators to develop muscle memory and learn the unique operating procedures of the aircraft

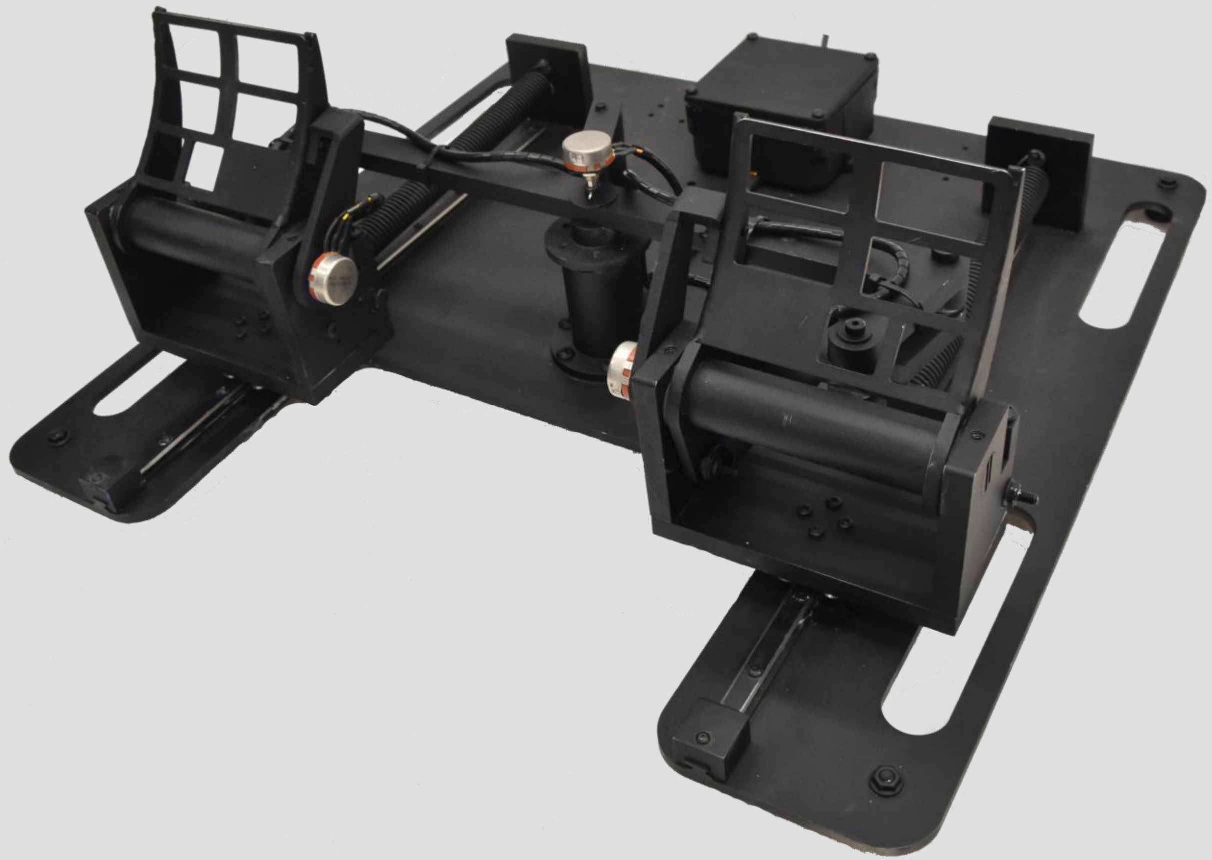
3D Printed Cockpit


Simulator Training Flight


Desktop Simulator

Francisco Lopez

Rudder Pedal System



- Rudder Pedal System (RPS): Controls the jet rudders, nose wheel steering and rear wheel brakes
- Initially developed by a previous senior design team, we integrated this RPS with minor modification

Francisco Lopez

HOTAS System

- HOTAS: Hands on Throttle and Stick
- Throttle: Controls the thrust from the jet engine
- Stick: Controls the pitch and roll axes of the aircraft
- Some aspects of the HOTAS from previous senior design team were incorporated in our version

Throttle

Stick

Francisco Lopez

Key Goals

Create finished, working prototype

Integrate physical sub-systems into the simulation software

Keep manufacturing costs low

Design for use in desktop or cockpit training models

Will Rickles

Flight Control Functions

Pilot Interface

- Controls closely mimic F-35 look and feel
- Mechanical parts will withstand repeated use

Communicate to Software

- Controller position awareness
- Negligible input delay
- Simulated jet accurately responds to control inputs

Will Rickles

Critical Targets

Cost
- Each new sub-system less than $1000

Latency
- No more than 20ms delay from input

Compatibility
- 3D printed cockpit and standard desk

Will Rickles

Additional Targets

Individual components < 35 pounds

Joystick deflection 13 degrees in all directions

Throttle travel 6 inches

Operates 1 hour without defect

No more than 15 lbf required to move RPS[1]

HOTAS withstands applied 7.5 lbf[2]

Will Rickles

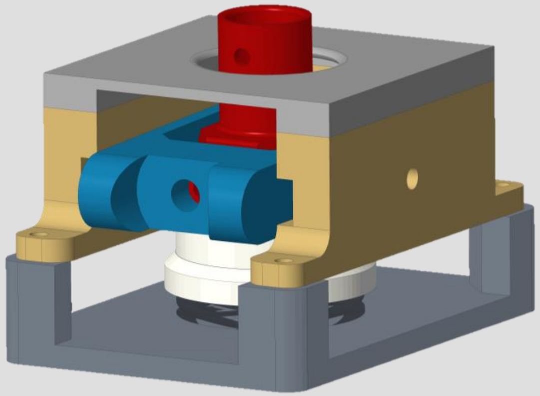
1. DoD Design Criteria Standard MIL-STD-1472H 5.1.4.2.2.2.9
2. DoD Design Criteria Standard MIL-STD-1472H 5.1.4.2.2.1.6

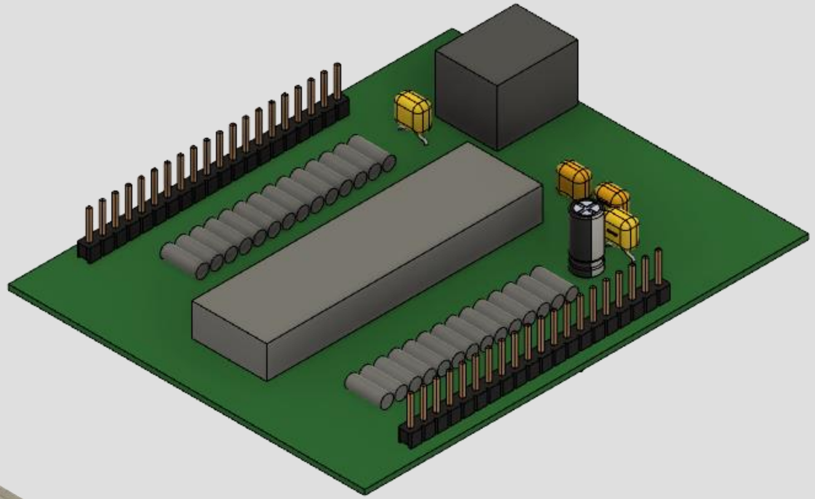
Final Design Selection

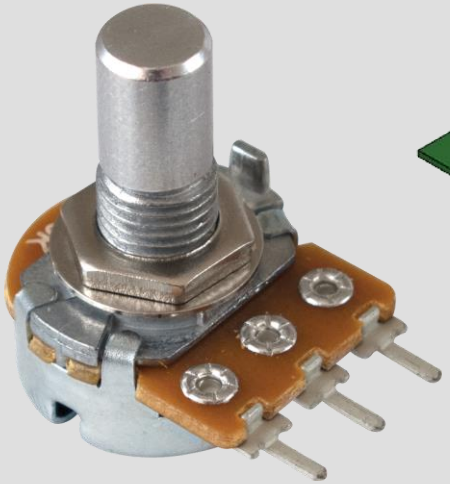
- Stick: 2-axis gimbal, rotary sensors, custom USB microcontroller

- Throttle: linear square rail, rack and pinion with rotary sensor, custom USB microcontroller

- Rudder Pedal System: updated rotary sensors, custom USB microcontroller







Will Rickles

Final Design Selection

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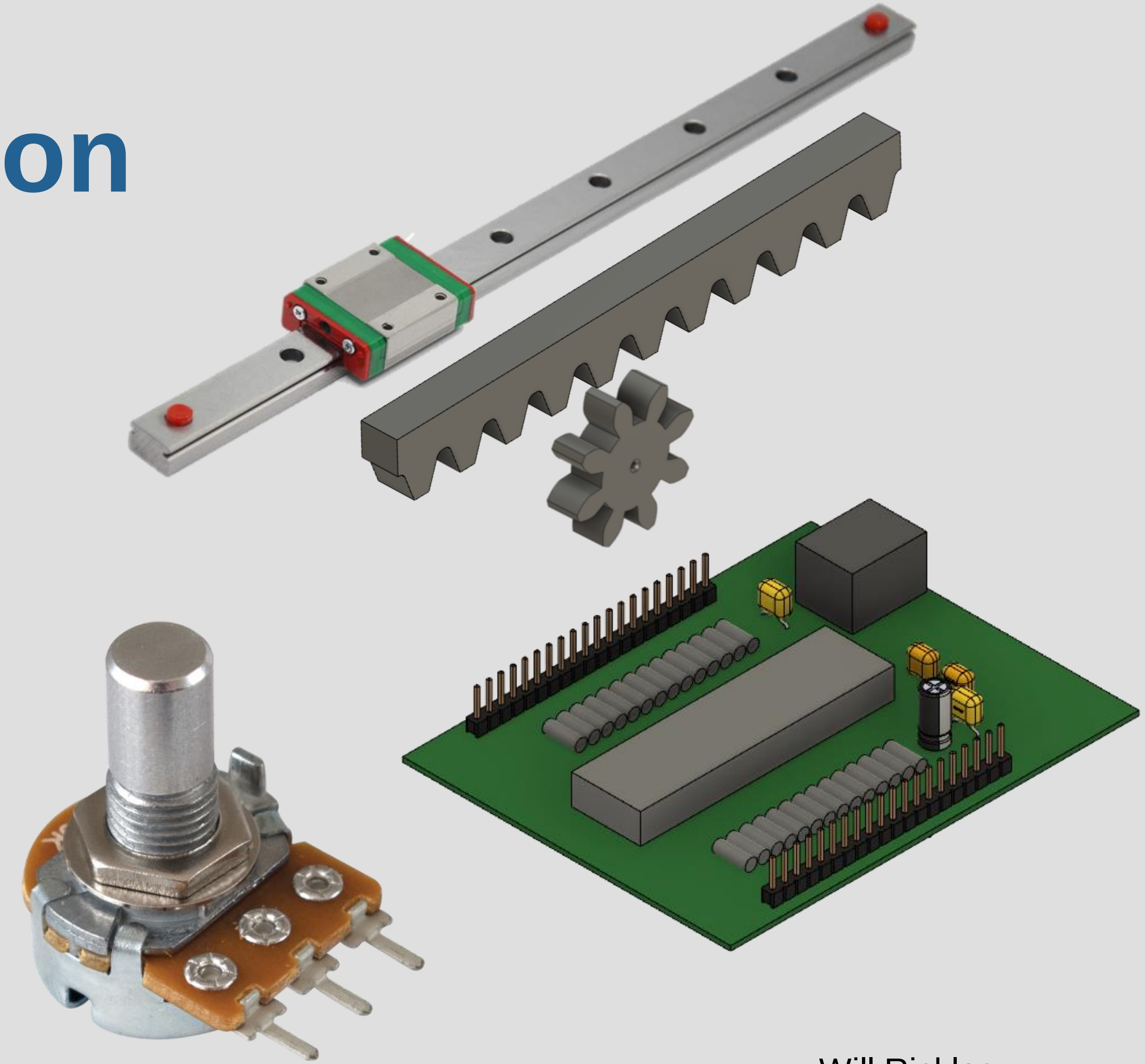

Will Rickles

Final Design Selection

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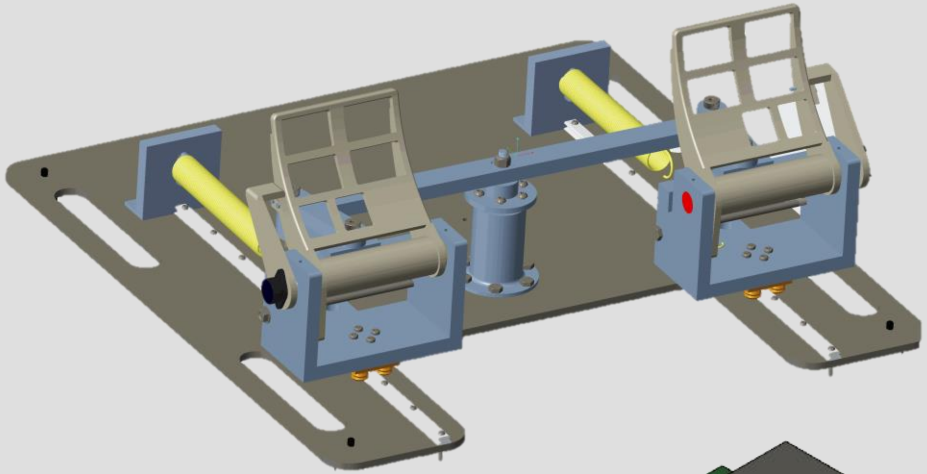
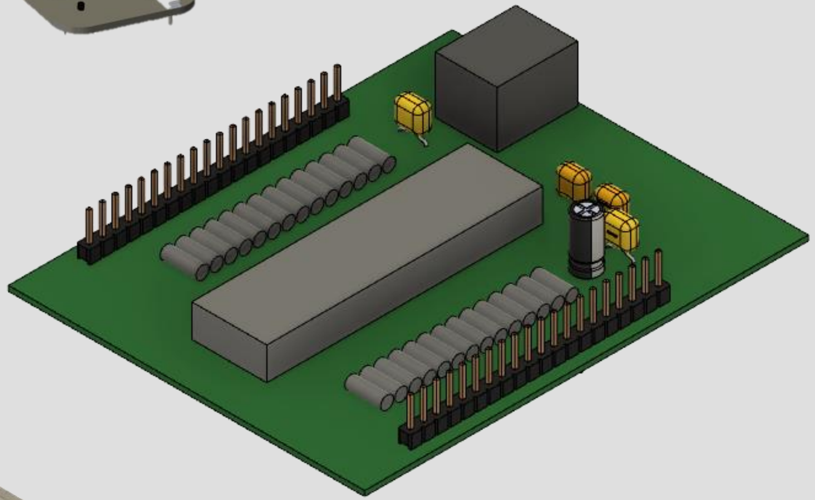
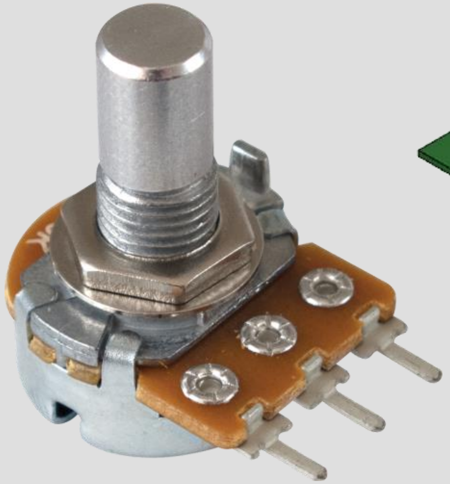
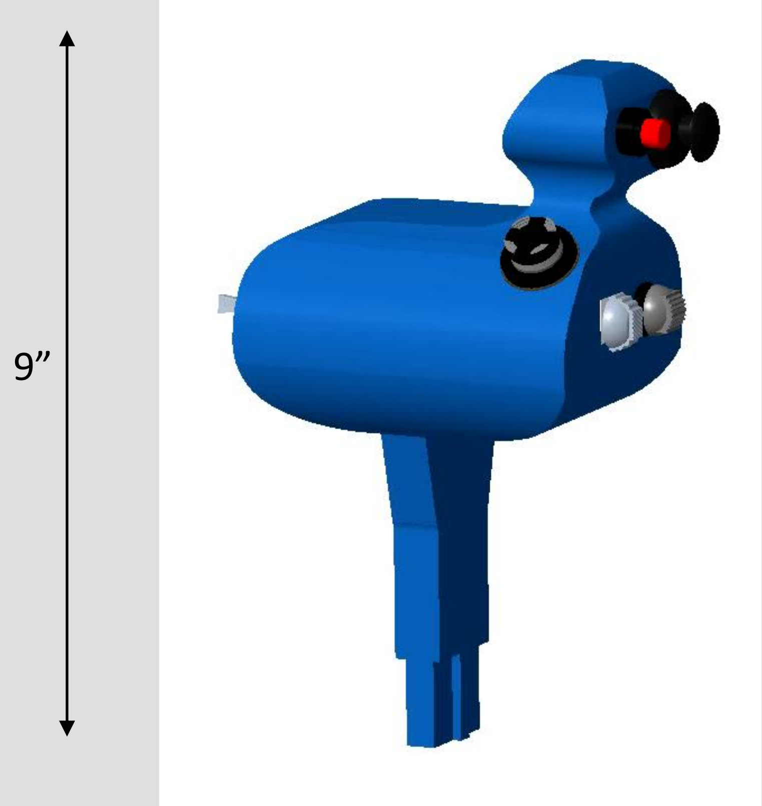




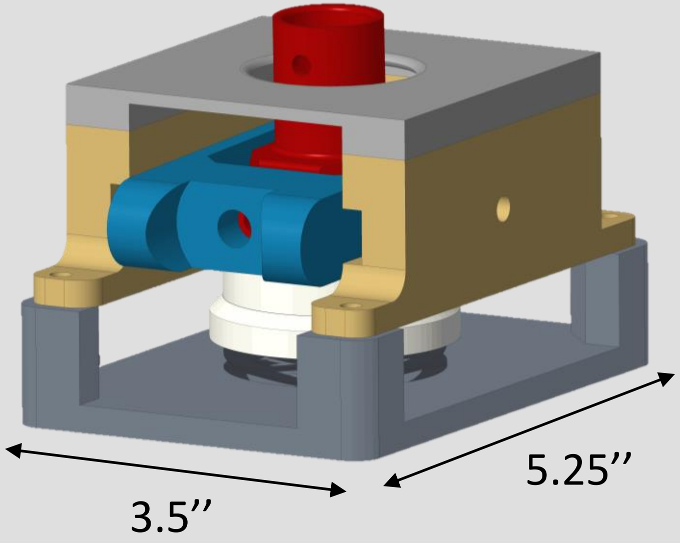


Will Rickles

Creating CAD Designs



Throttle



Joystick Gimbal

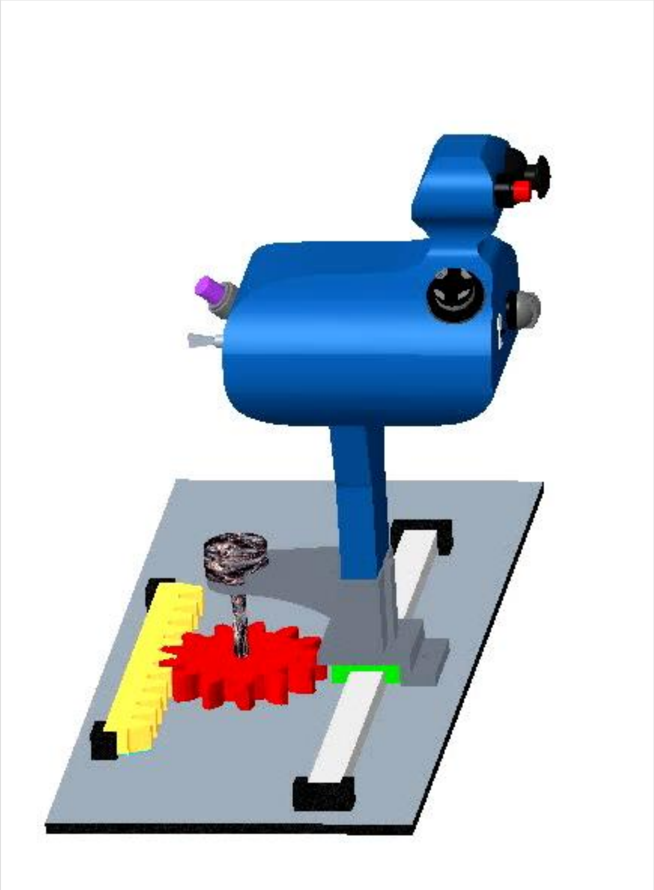
Joystick

Branden Pacer

*2012 Anthropometric Survey of U.S. Army Personnel TR-15/007

Throttle Mechanism

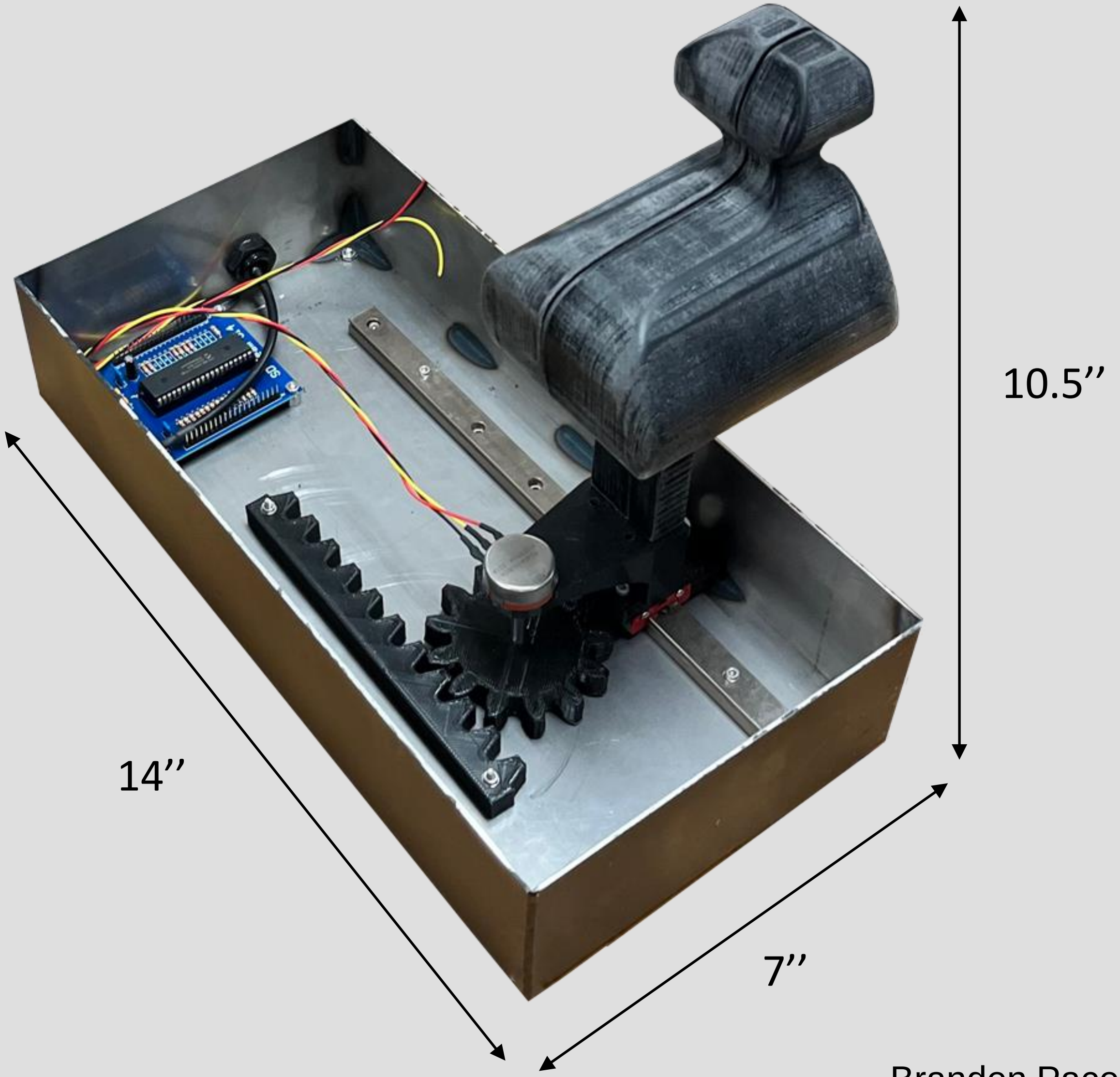
- Rack and pinion utilized to sense linear displacement
- Nylon screw in slider attachment provides adjustable resistance
- Linear square rail resists axial moment



Branden Pacer

Throttle Prototype

- Prototype Results
  - Rack and pinion are 3D printed
  - Welded steel enclosure with a removable lid
  - Wires are constrained to left side of box



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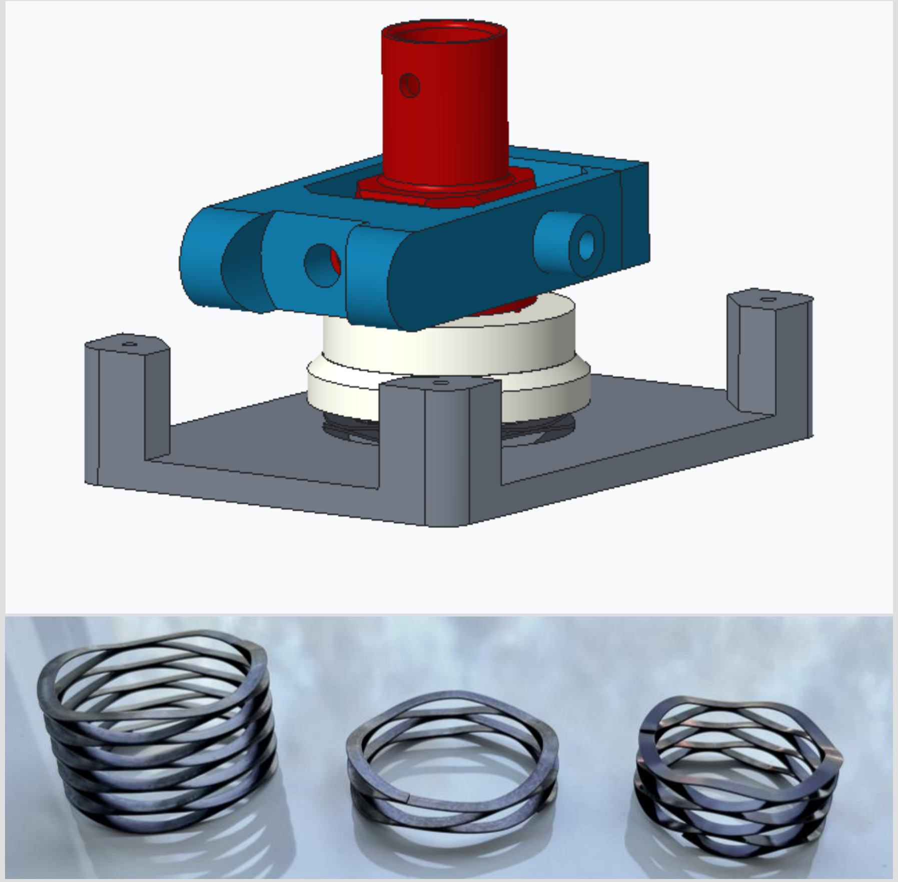
Joystick Mechanism



- Gimbal allows motion within target angle of deflection
- Single wave spring provides joystick resistance
- Wave springs reduce overall height of stick

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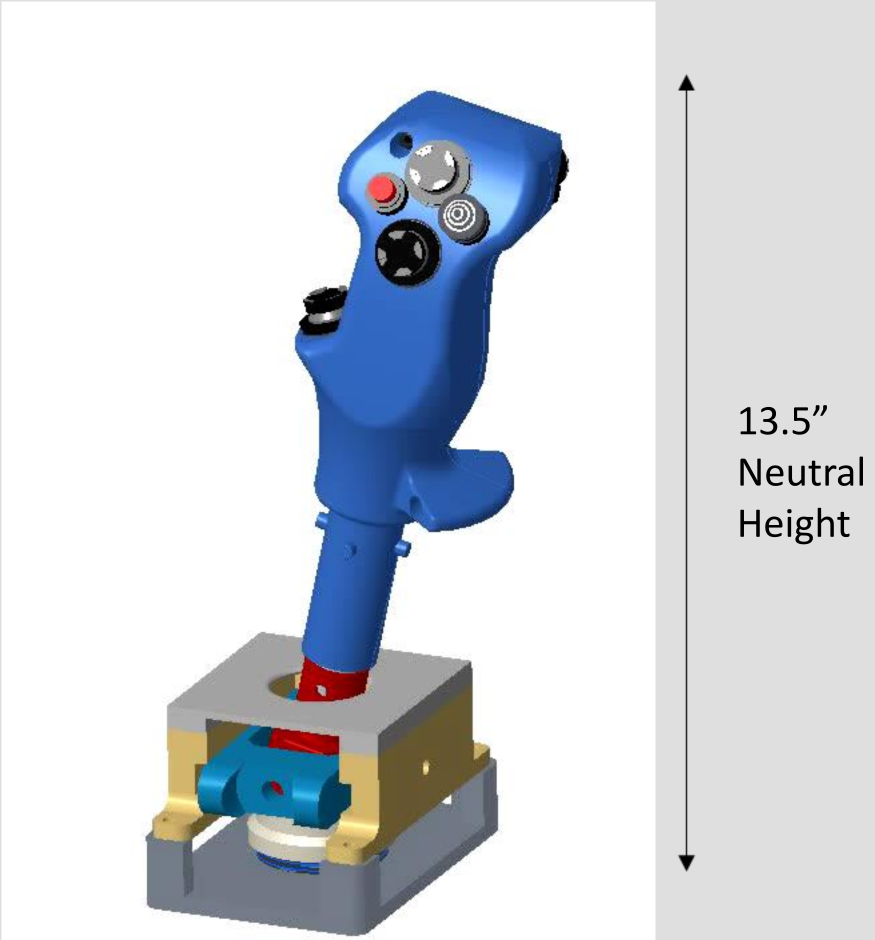
Joystick Mechanism

- Challenges creating smooth joystick control
  - Contact surfaces
  - Spring force and deflection
  - Integrating large rotary sensors
  - Centering of gimbal



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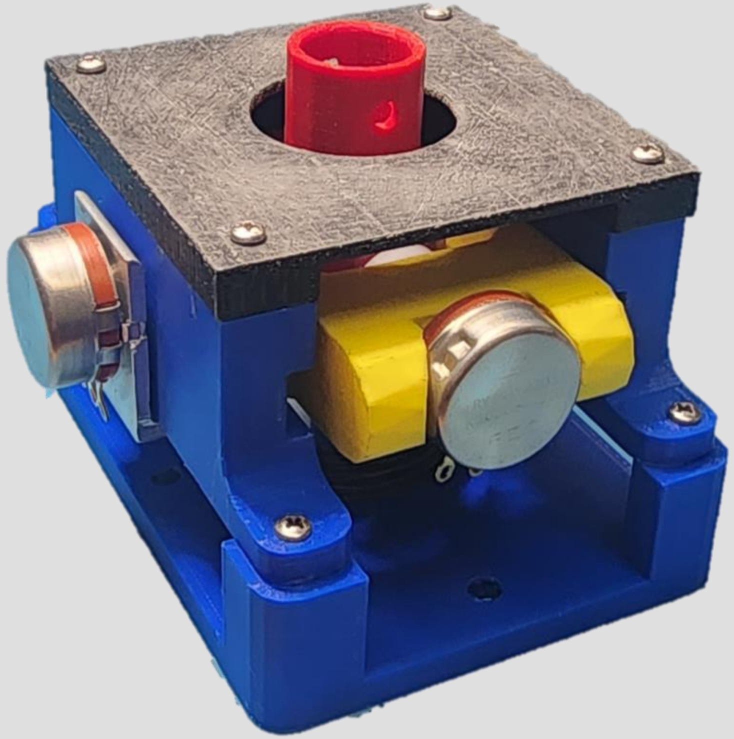
Joystick Prototype

- Results:
  - Reasonably smooth
  - Does not create distraction
  - Rotary sensors have plenty of wire clearance
  - Options available for increased resistance



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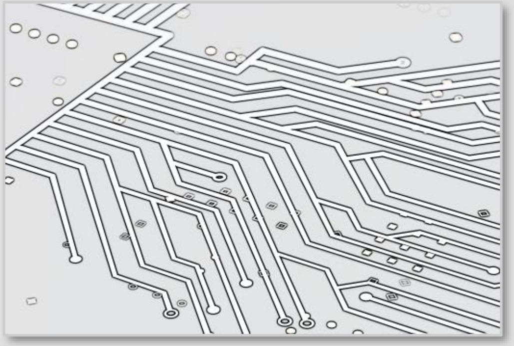
Electronics Design



Constraints

- Lots of buttons, switches, and rotary sensors need to connect to the simulator
- Communication must be fast
- Compatible with lots of computers
- Requested not to use Arduino as previous teams did

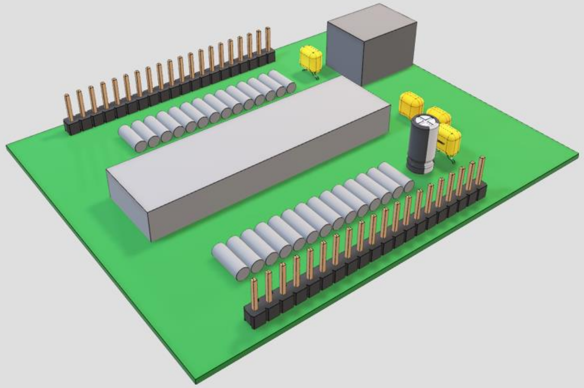
Signals

- Joystick:
  - 10 buttons, multi-position switches
  - 2 rotary sensors
- Throttle:
  - 11 buttons, multi-position switches
  - 3 rotary sensors
- Rudder Pedal System:
  - 3 rotary sensors

Jonah Gibbons

Electronics Solution

- PIC microcontroller:
  - 40 connection pins to use
  - 13 analog-to-digital channels
  - Powered by USB port
  - Low-cost
- Custom firmware:
  - Code written specifically to process our signals and transmit them efficiently over USB
- Custom printed circuit board:
  - Built to match our exact needs for circuit components



Jonah Gibbons

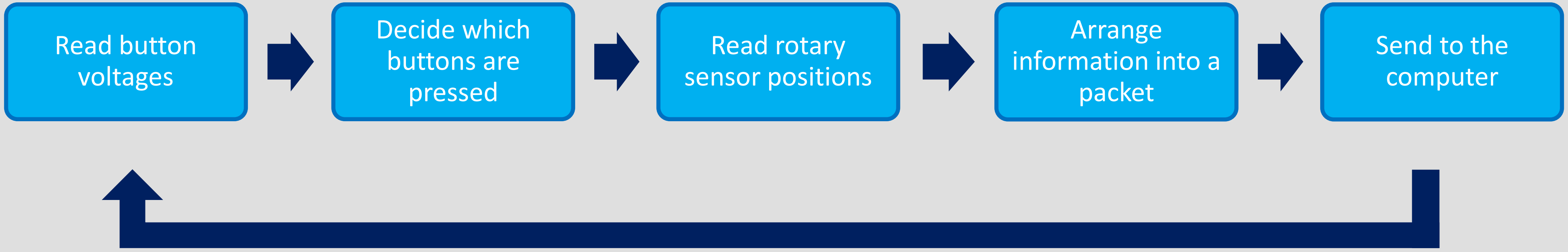
Universal Serial Bus (USB)

- Designed to be plug-and-play solution for any electronic device
- Capable of high-speed data transfer
- Generic drivers are standard on computers now

Jonah Gibbons

**Reference* – *USB v2.0*, USB Implementer's Forum, https://usb.org/usb2

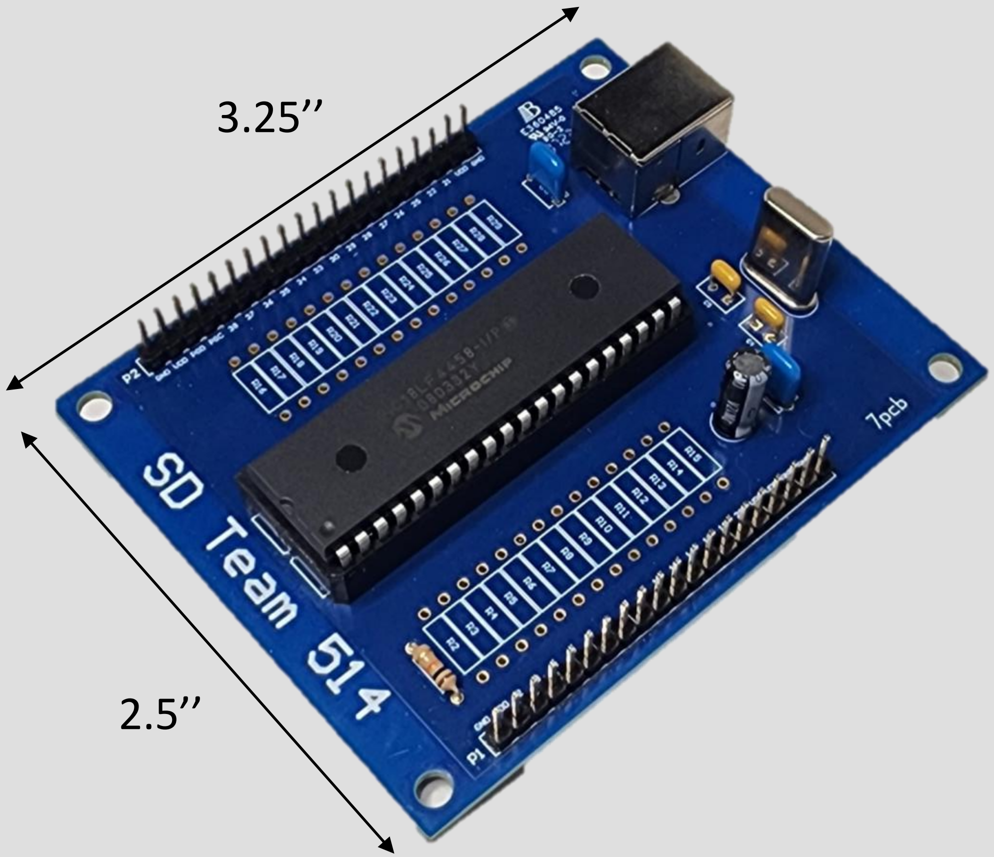
Firmware



- 732 lines of code not including USB header files
- Written and compiled using Microchip's MPLAB X software

Jonah Gibbons

Custom Printed Circuit Board

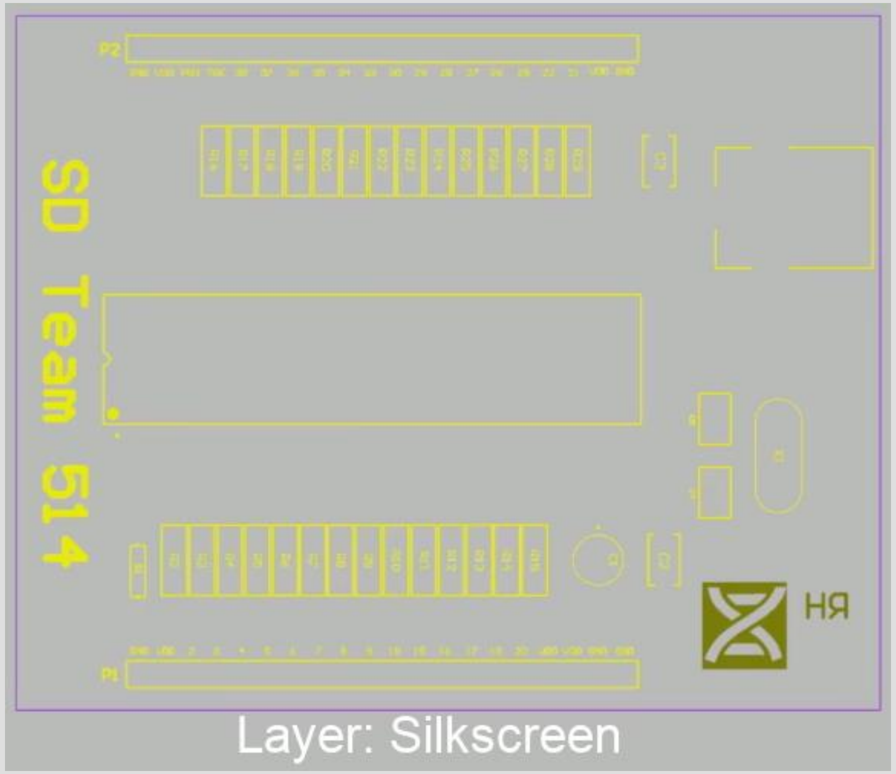


Creating our own PCB from scratch allowed us to design it for our exact needs

Jonah Gibbons

Custom Printed Circuit Board

- 5-layer design
  - Separate signal layers
  - Sandwich traces between ground planes to reduce signal noise (electro-magnetic interference)
- Same layout used for all 3 controllers



Jonah Gibbons

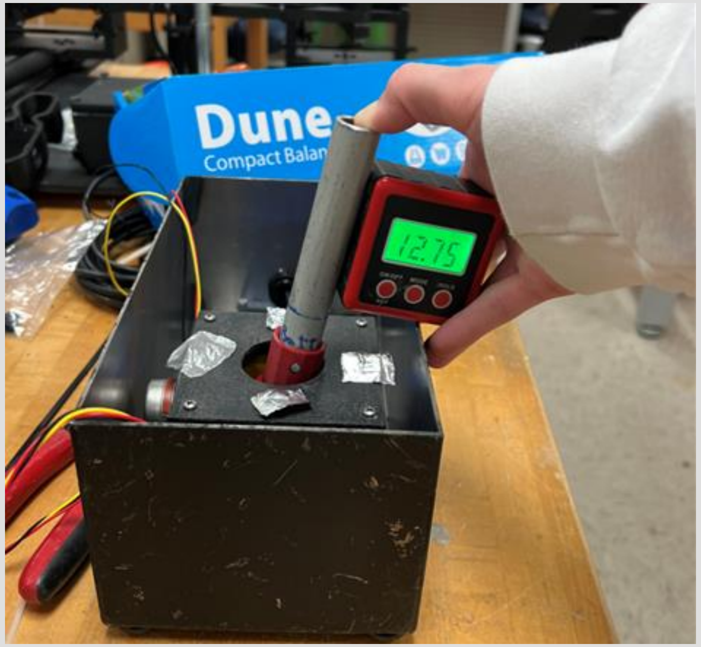
Methods of Validation

- Joystick Deflection
  - Inclinometer
- Latency
  - Smart Phone, Tripod, Millisecond Clock
- Force Required to Deflect Rudder Pedals
  - Force Gauge
- Force Required to Deflect HOTAS
  - Force Gauge

Laiken Kinsey

Joystick Validation

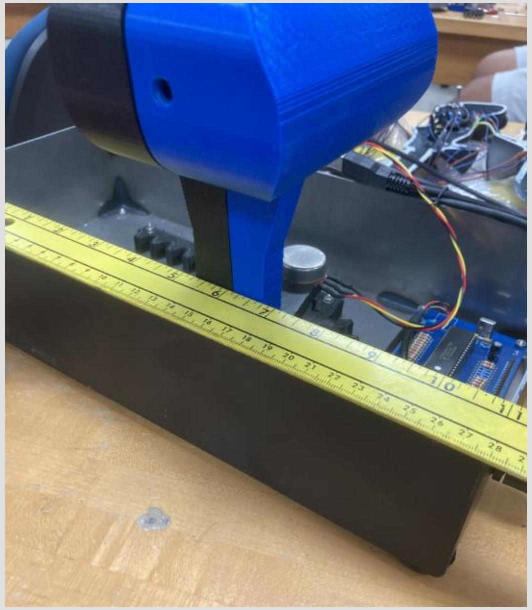
- Angle of deflection
  - **Goal: 13°**
  - Forward: 12.7°
  - Backward: 13.9°
  - Left: 14.7°
  - Right: 13.3°
- Resistance to deflection
  - **Goal: <7.5 lbf**
  - Pitch: 1.3 lbf
  - Roll: 1.5 lbf
- Downward Force Test
  - Highest tested: 24.2 lbf



Laiken Kinsey

Throttle Validation

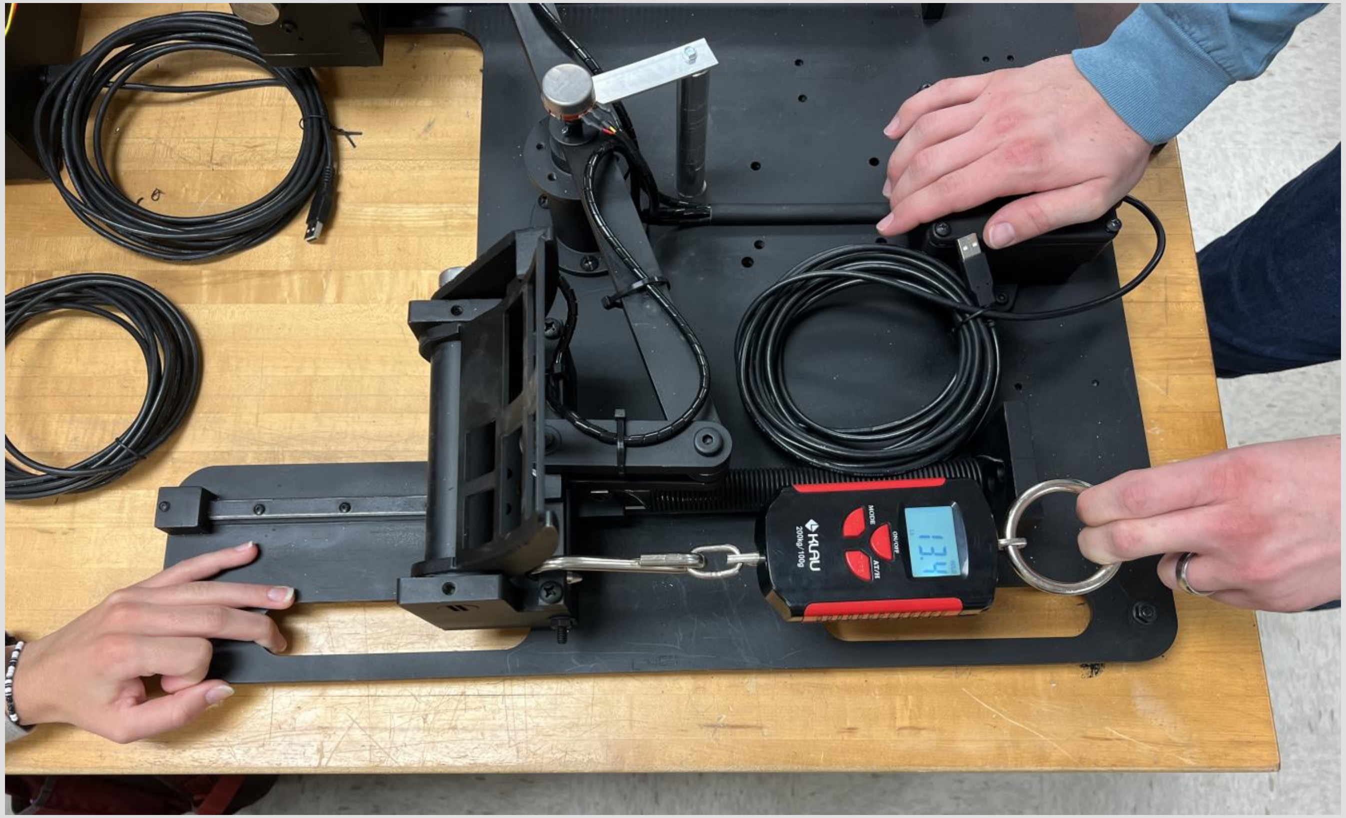
- Travel Distance
  - **Goal: 6 in**
  - Distance: 6.06 in
- Resistance to motion
  - **Goal: <7.5 lbf**
  - Resistance: 0.75 lbf
- Downward Force Test
  - Highest tested: 26.5 lbf



Laiken Kinsey

RPS Validation

- RPS Weight
  - **Goal: <35 lbs**
  - Weight: 25 lbs
- Force of deflection
  - **Goal: <15 lbf**
  - Left pedal: 11.2 lbf
  - Right pedal: 13.5 lbf



Laiken Kinsey

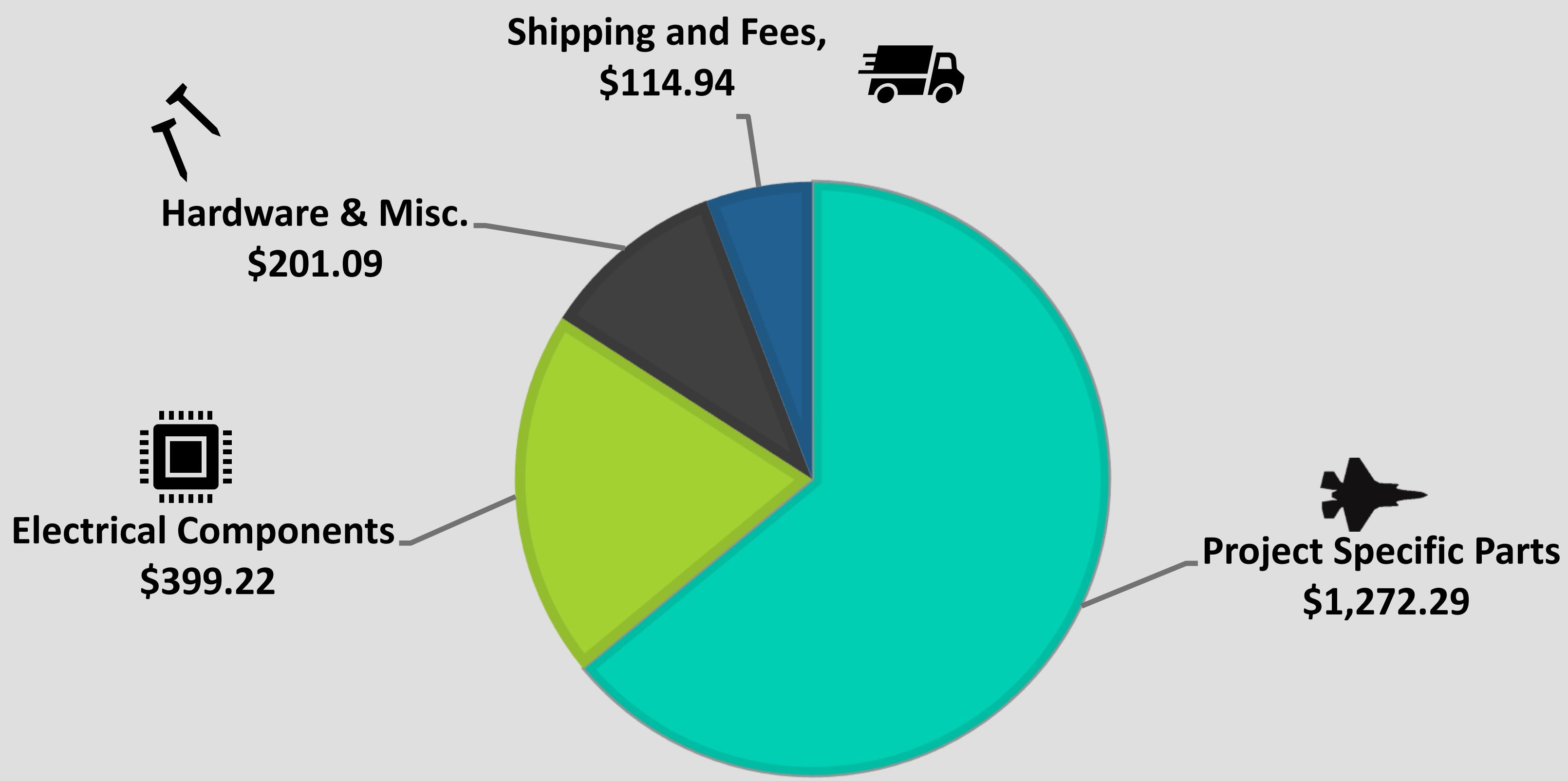
Latency and Bit Rate

- Latency
  - **Goal: 20 ms → 350 ms**
  - Average: 180 ms
- Bit Rate
  - **USB v2.0 Full Speed mode: 12 Mb/s**

Laiken Kinsey

Budget

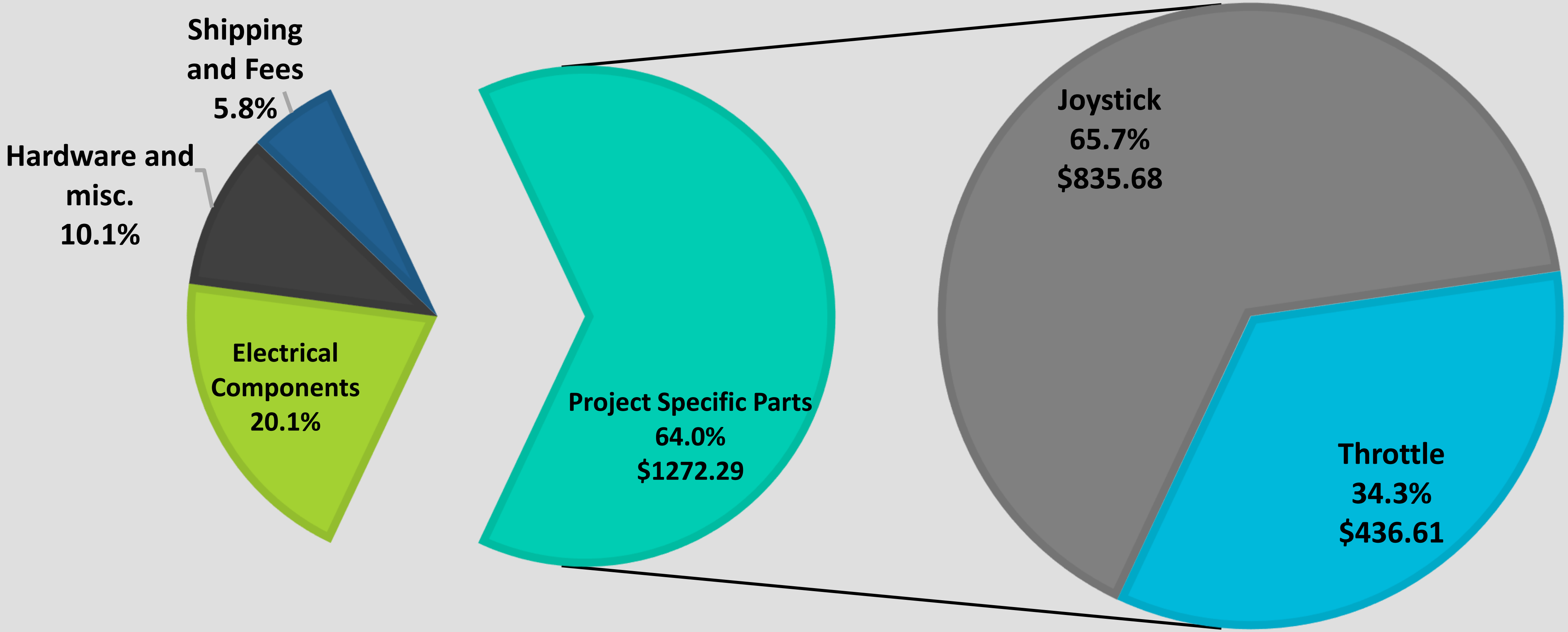
TOTAL COST TO DATE:
$1987.54
99.38% OF OVERALL BUDGET



- Project Specific Parts : 64.0%
- Electrical Components : 20.1%
- Hardware and misc. : 10.1%
- Shipping and Fees : 5.8%

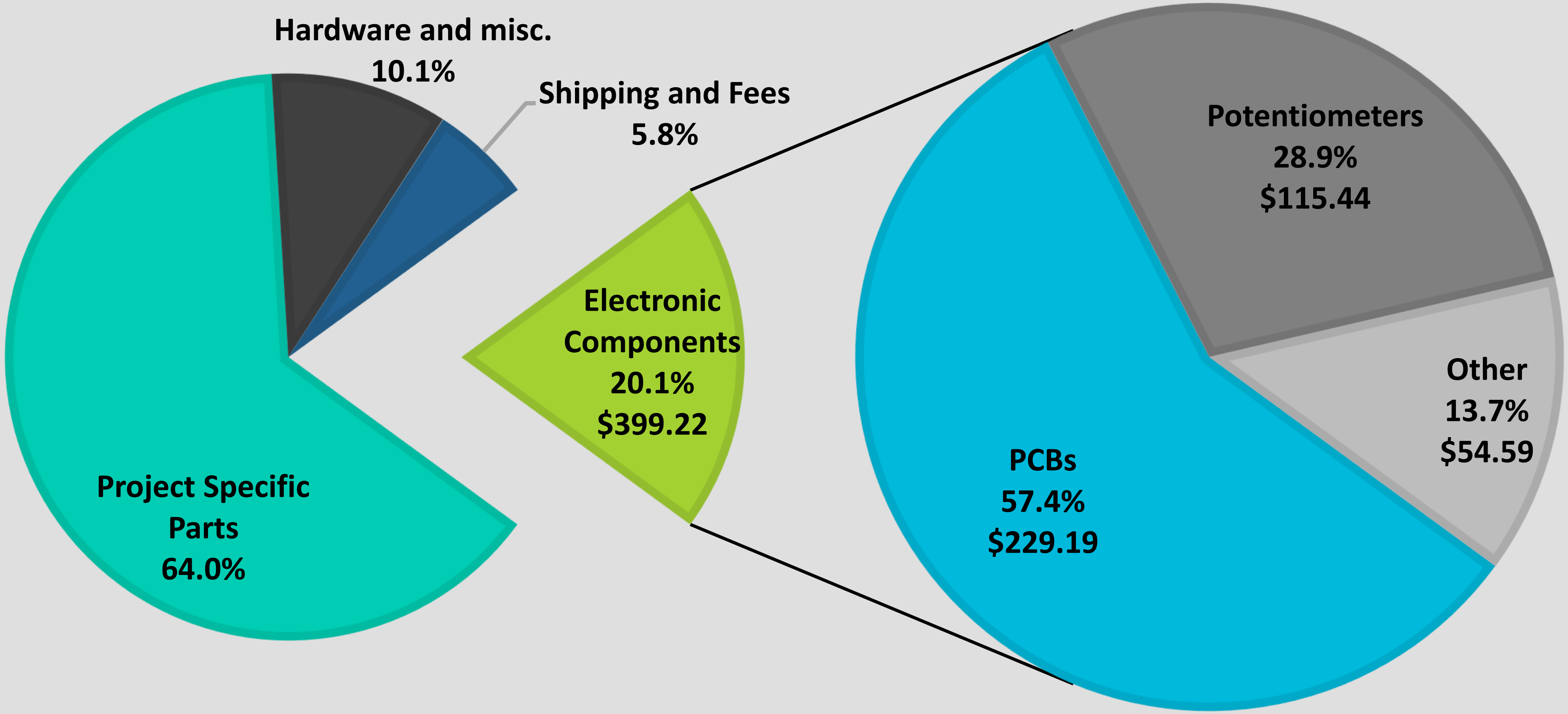
Emelia Rodriguez

Budget



Emelia Rodriguez

Budget



Emelia Rodriguez

Summary

- Objective
  - Create F-35 controls for low-cost simulation training
- Targets
  - Working desktop prototype created within $2000 limit
- Design
  - Two subsystems built new, RPS improved
- Outcome
  - Flight tests have been successful, and system is fully integrated

Emelia Rodriguez

Final Demonstration

- Demonstrations completed:
  - Normal Takeoff and Landing
  - Short Takeoff and Landing
  - Vertical Takeoff and Landing
  - Aerobatic Flight Maneuvers

Emelia Rodriguez

Lessons Learned

Be sure to assemble prototypes early so there is ample time for adjustments or redesigns

Defend your ideas but remain flexible and open-minded toward necessary changes

With multiple iterations, version control is essential when collaborating on parts with teammates

Joining 3D prints together can be tricky, so plan for wide tolerances and other ideas like hardware

Parts lock up, wear out, and break, so budget for maintenance as well

Keep tabs on everything because having a broader project awareness speeds everything up

Emelia Rodriguez

Questions?

Design Team	Project Objective	Goals	Target Metrics
Concept Selection	Designs	Electronics	Test Methods
Validation	Budget	Summary	Demonstration

Emelia Rodriguez

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Early Prototypes

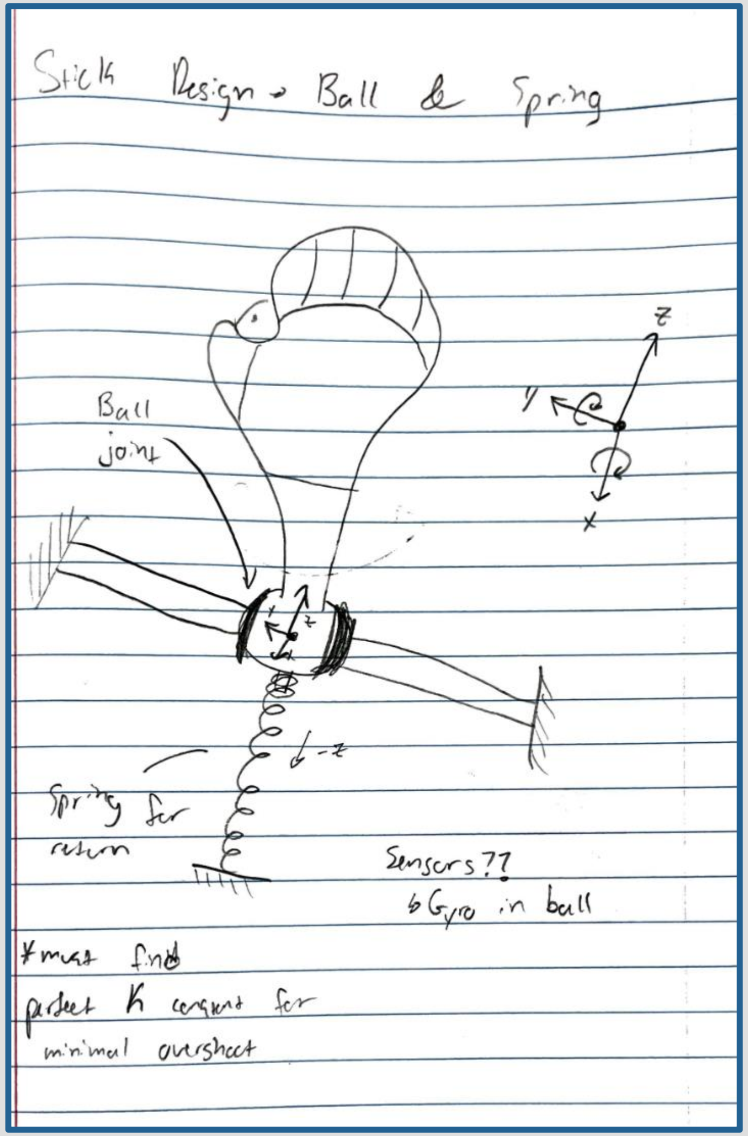
Branden Pacer

Concept Generation

<u>Joystick High Fidelity Concepts</u>:

Single-spring, ball joint— a ball in a socket with a single spring below to keep the neutral position upright

- The design is simpler to construct and easier to support from downward forces of pilot's hand
- Much harder to measure the joystick position with sensors



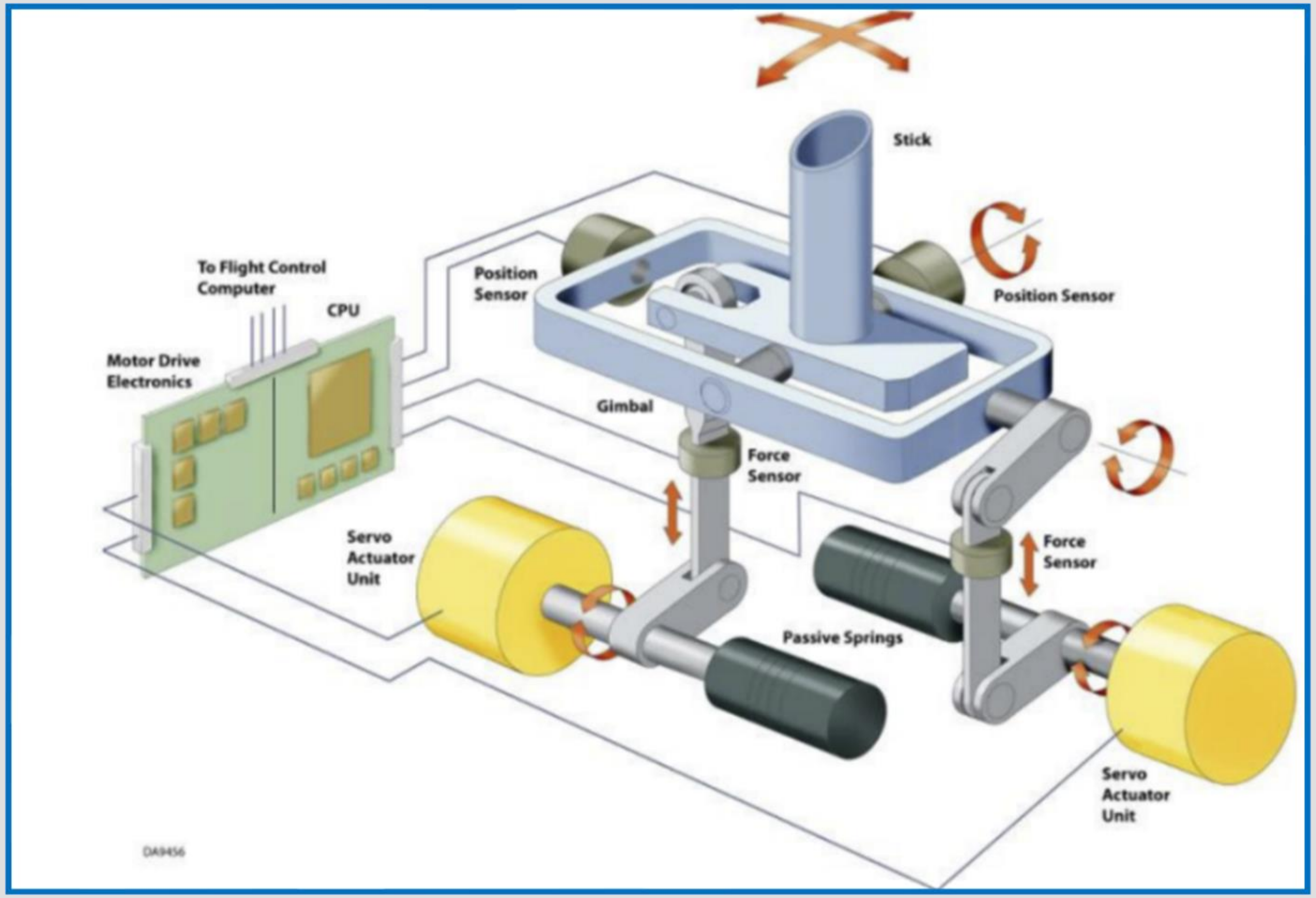
Branden Pacer

Concept Generation

<u>Joystick High Fidelity Concepts</u>:

Multi-plane gimbal— two-piece gimbal with axels connected to rotary sensors with individual springs to keep the neutral position upright

- This requires more intricate pieces to construct but is identical to the actual construction in an F-35 jet
- Linkages make it easier to measure position



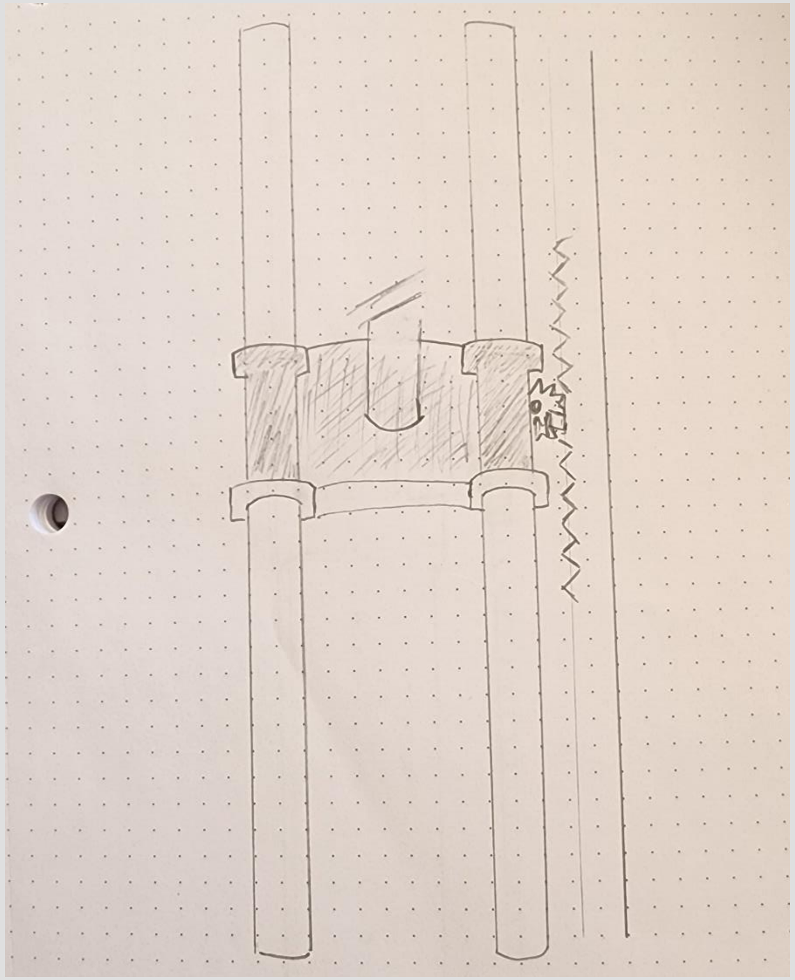
Branden Pacer

Concept Generation

Throttle High Fidelity Concepts:

Multiple, tube rails— the throttle handle will slide along two parallel rails

- This concept was considered in order to resist the risk of torque damage and instability that a single tube rail would have
- Requires a lot of “from-scratch” design work on the cart and its bearings



Branden Pacer

Concept Generation

Throttle High Fidelity Concepts:

Single, rectangular rail— the throttle handle will slide along a single rail with ball bearings in the grooves

- This concept is very high-strength and the construction eliminates concerns of torque damage and excessive wear
- It is pre-manufactured and low cost

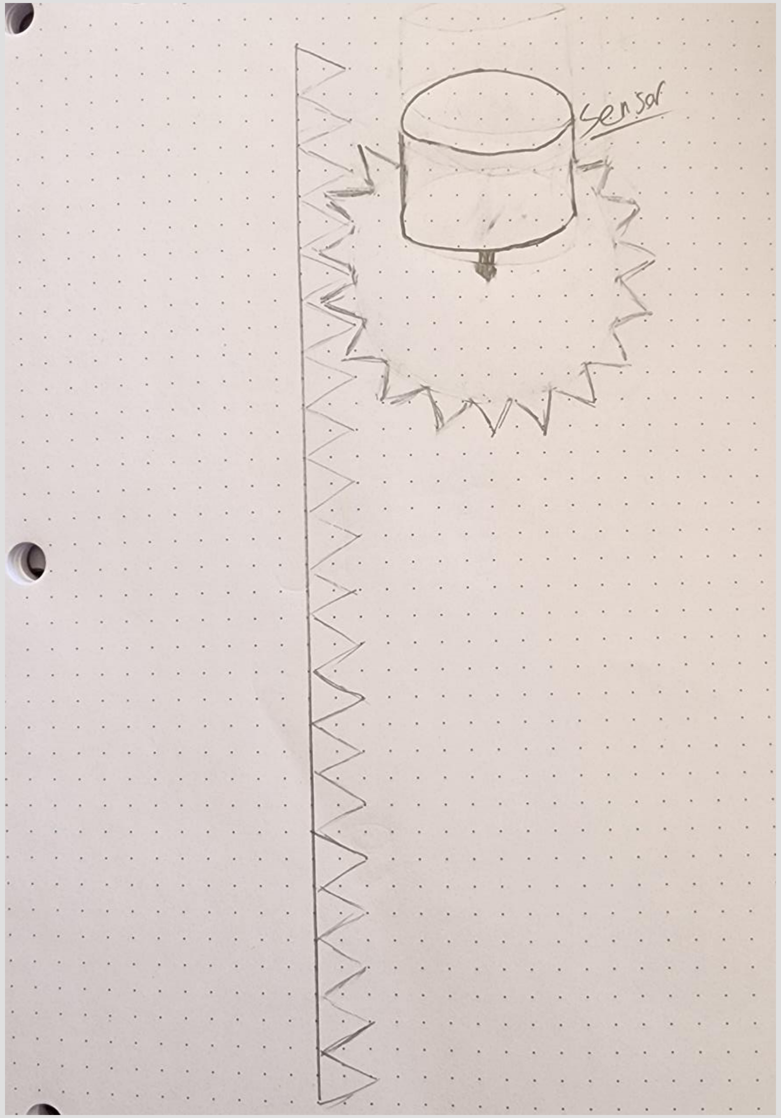
Branden Pacer

Concept Generation

<u>Throttle Position Concepts</u>:

Gears: rack and pinion— the sensor would be attached to a rack and pinion to actuate it when the throttle is moved

- This concept is very simple and durable



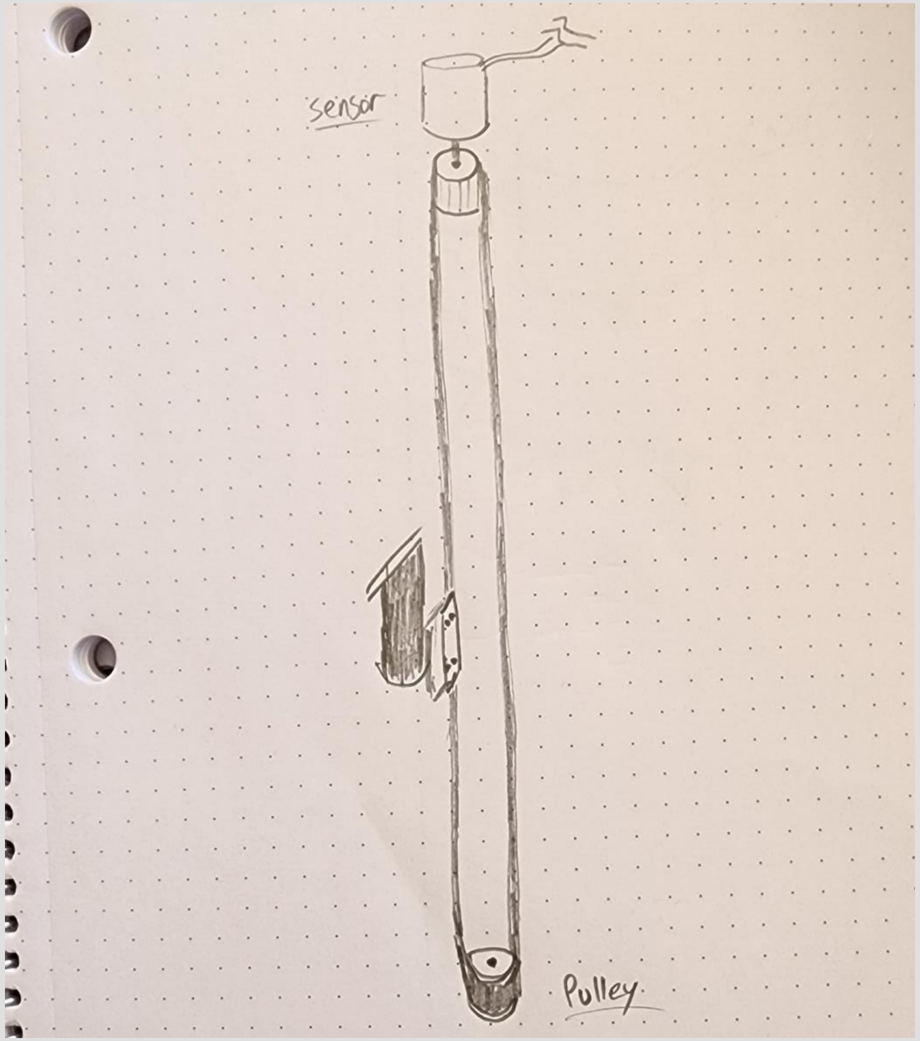
Branden Pacer

Concept Generation

Throttle Position Concepts:

Belt actuated— the sensor would be attached to a pulley with a belt around it which is fixed to the cart, moving with the throttle handle

- This concept is could be tricky to design from scratch and requires more maintenance and adjustable tensioning



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Concept Generation

Sensor High Fidelity Concepts:

Rotary Hall Effect— measures the strength of a magnetic field from a permanent magnet which moves inside

- Because the sensor doesn't rely on mechanical contact, it has a longer lifespan
- The sensors cost more

Rotary Hall Effect Sensor

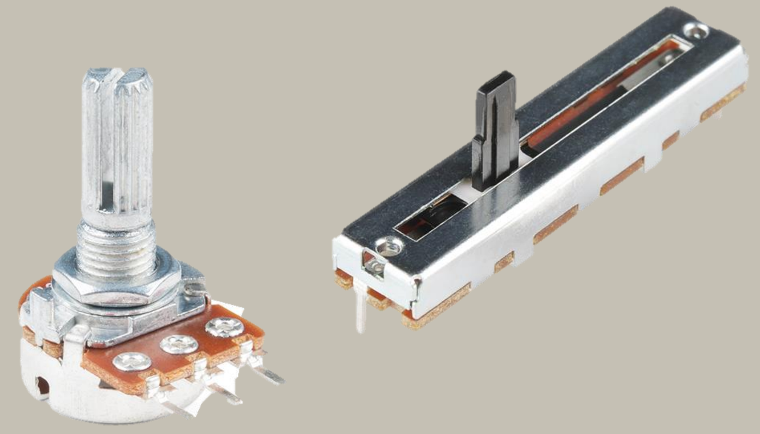
Branden Pacer

Concept Generation

<u>Sensor High Fidelity Concepts</u>:

Potentiometer— contains a wound resistive element and a wiper contact which moves along the element providing a variable level of resistance

- They are very low cost, standard, and easy to implement

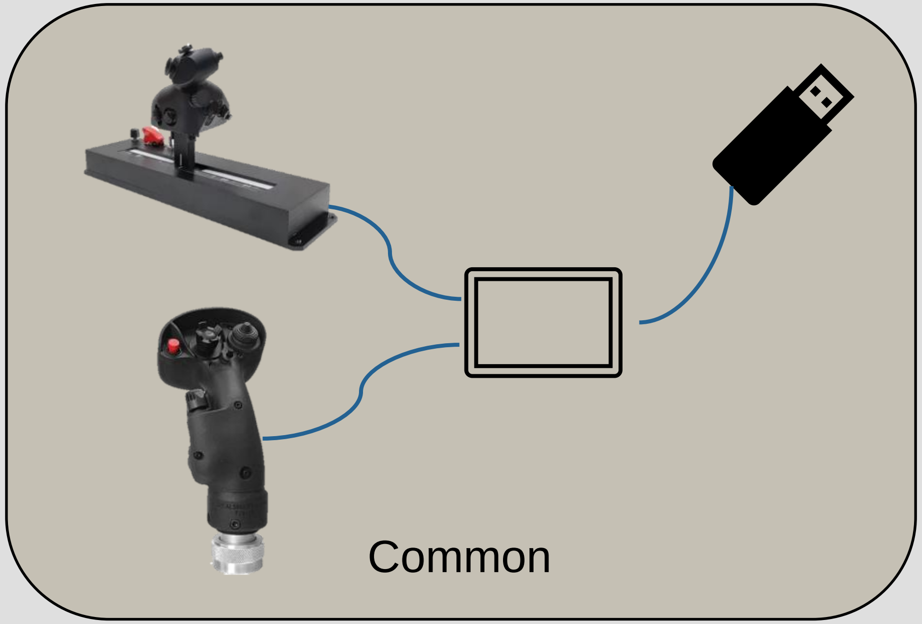


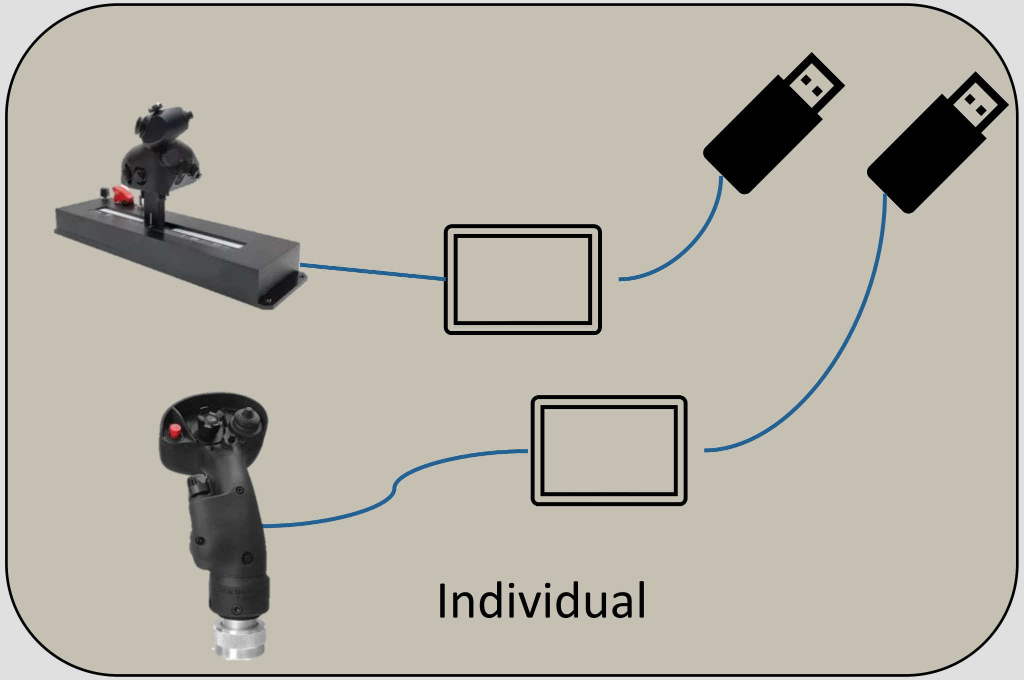
Potentiometers

Branden Pacer

Concept Generation

- Microcontroller Options
  - Individual controllers
  - Common controller





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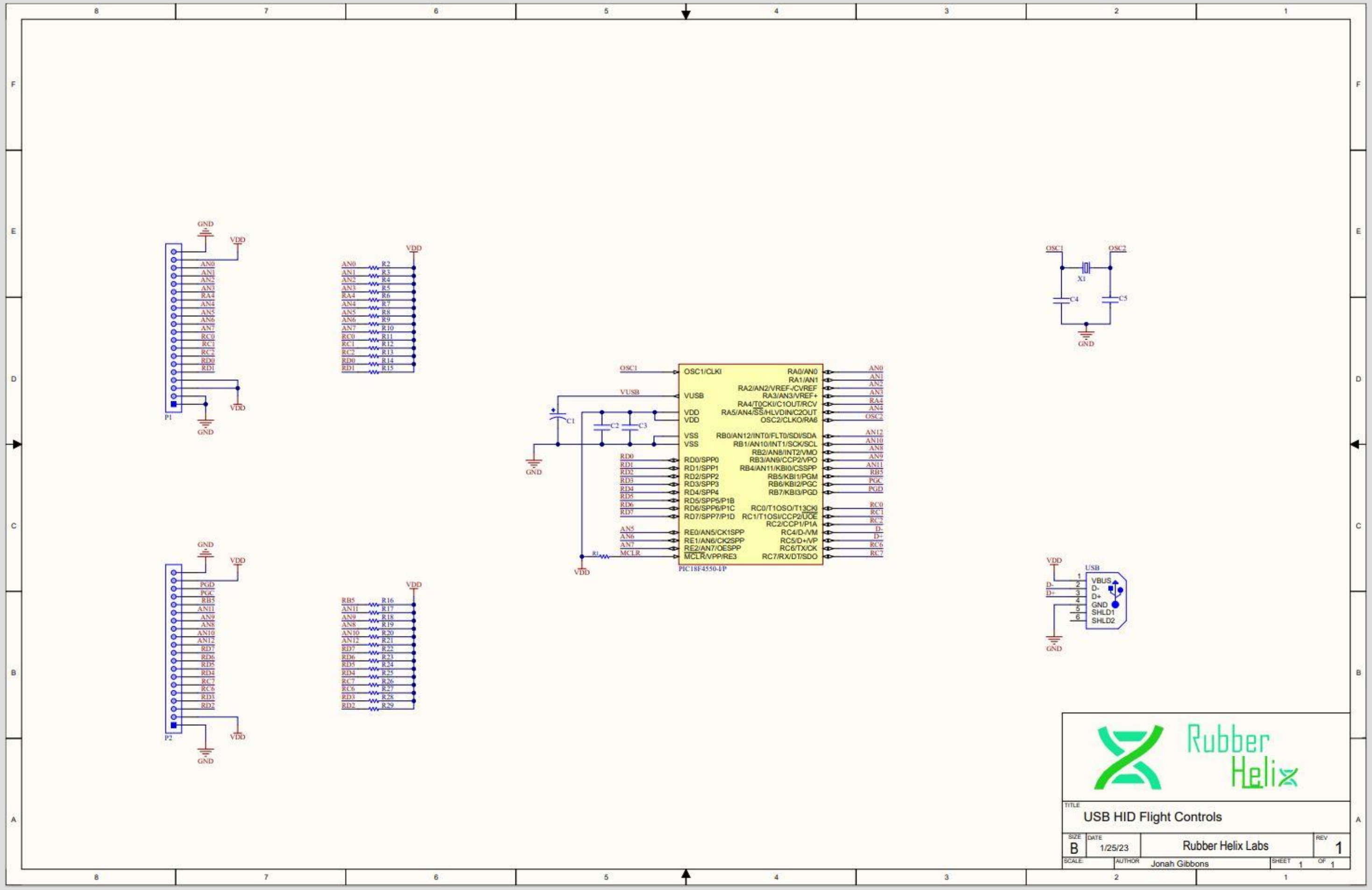
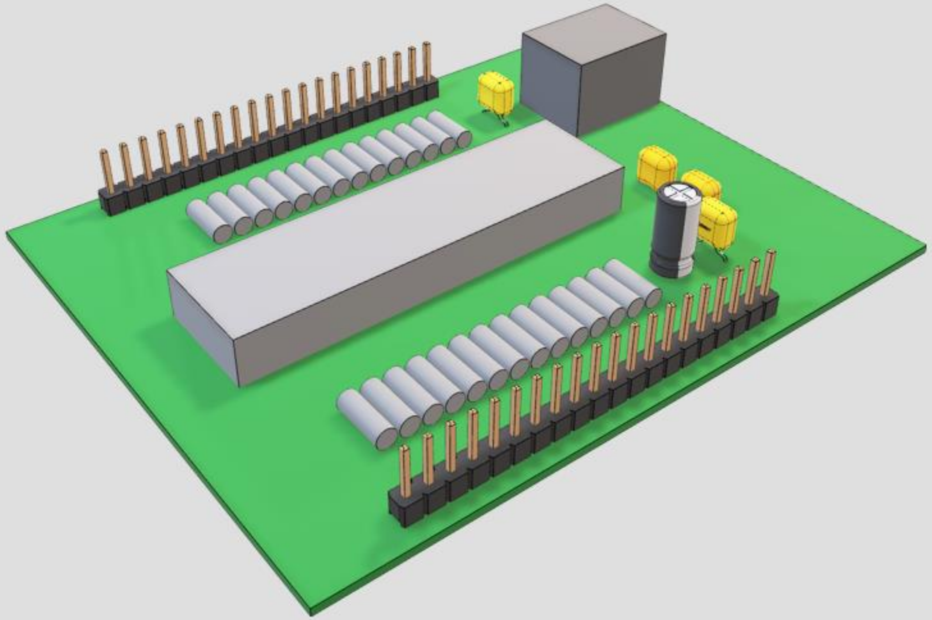
Printed Circuit Board Schematic



Jonah Gibbons

PCB Validation

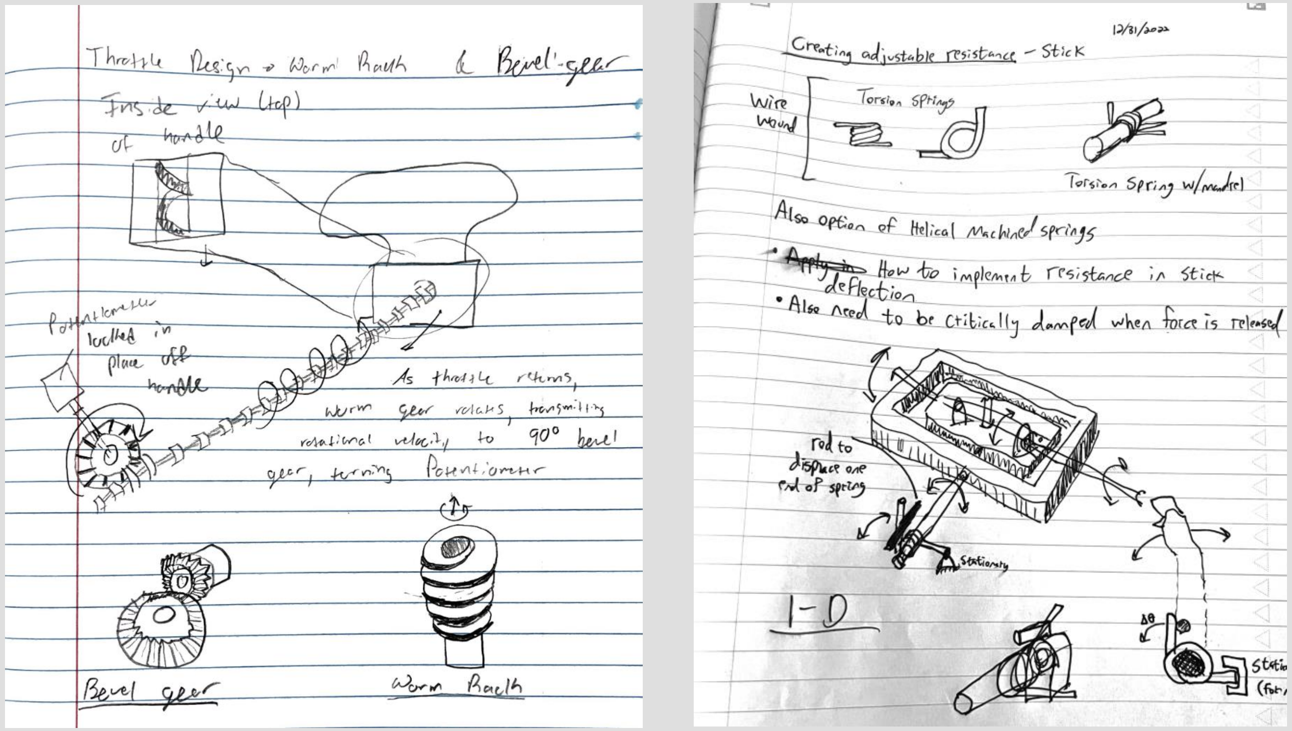
- Electric Test Report
  - **Test voltage - 250 V**
  - **Test current – 100 mA**
  - **Conductive Resistance – 20 Ω**
  - **Insulation Resistance - 20 MΩ**
- Solderability Test Report
  - **245 +/- 5 °C for 3-5 seconds**
- Thermal Stress Test Report
  - **288 +/- 5 °C for 10 seconds**



Laiken Kinsey

Concept Generation

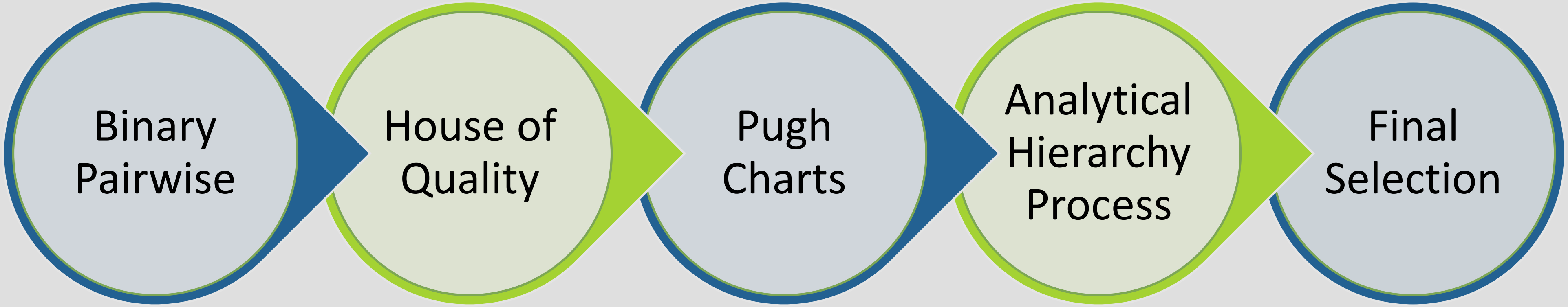
- Joystick:
  - Multiplane gimbal
  - Ball joint
  - Linkages
- Throttle:
  - Rack and pinion gears
  - Belt system
  - Worm and bevel gear
- RPS:
  - Upgrade electronics
  - Keep previous electronics system



Preliminary Sketches

Emelia Rodriguez

Concept Selection Process



Branden Pacer

Binary Pairwise Comparison

	1	2	3	4	5	6	7	8	9	Total	IWF
1. Cheap to manufacture	-	1	0	1	0	1	0	1	1	5	4
2. Fits into desk and cockpit model	0	-	0	0	0	1	0	1	1	3	2
3. Equipment fully integrated with Prepar3D	1	1	-	1	0	1	1	1	1	7	5
4. Will be able to simulate flying a box	0	1	0	-	0	1	0	1	1	4	3
5. Complete, polished prototype	1	1	1	1	-	1	1	1	1	8	5
6. Components provide appropriate resistance	0	0	0	0	0	-	1	1	0	2	2
7. Provides accurate in-flight feel for F-35	1	1	0	1	0	0	-	1	0	4	3
8. Lower mechanical complexity	0	0	0	0	0	0	0	-	1	1	1
9. Withstand vigorous use	0	0	0	0	0	1	1	0	-	2	2
Total	3	5	1	4	0	6	4	7	6	n-1=8	

William Rickles

House of Quality

HoQ	Improvement direction	↑	↓	↑		↓	↓	↓	↓	↑
	Units	psi	s		lbs	$	integer	in	hours	
Customer Requirements	IWF	Material stength	Latency	Accuracy of position sensing	Applied resistance	Cost of Materials	Number of parts	Deviation from given dimensions	Time to complete	Aesthetics
Cheap to manufacture	4	1				9			1	
Fits into desk and cockpit model	2						1	9		
Equipment fully integrated with Prepr3D	5		9	9						
Will be able to simulate flying a box	3		3	9						
Complete, polished prototype	5								3	9
Components provide appropriate resistance	2	3			9					
Provides accurate in-flight feel for F-35	3		3	9	9			1		
Lower mechanical complexity	1						9			
Withstand vigorous use	2	9			3					
Raw Score (373)		28	63	99	51	36	11	21	19	45
Relative Weight %		7.5	16.9	26.5	13.7	9.7	2.9	5.6	5.1	12.1
Rank Order		6	2	1	3	5	9	7	8	4

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Pugh Chart

Selection Criteria	Datum	Concepts							
	Current LM F35 Sim "Wraith"	1	2	3	4	5	6	7	8
Accuracy of Position Sensing		-	+	-	+	-	-	-	-
Latency		+	+	-	-	+	+	-	-
Applied Resistance		-	-	-	+	-	+	-	+
Aesthetics		+	-	S	S	+	-	S	S
Cost of Materials		+	+	+	+	+	+	+	+
Material Strength		-	-	-	-	-	-	-	-
# of pluses		3	3	1	3	3	3	1	2
# of minuses		4	3	4	2	4	3	4	3

Concept	electrical	throttle	joystick	rps
1	hall & individual	single	ball	use existing
2	hall & individual	single	gimbal	use existing
3	hall & common	single	ball	use existing
4	hall & common	multi	gimbal	use existing
5	pot & individual	single	gimbal	use existing
6	pot & individual	multi	gimbal	use existing
7	pot & common	single	gimbal	use existing
8	pot & common	multi	gimbal	use existing

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Pugh Chart

Selection Criteria	Datum	Concepts					
	Past year projects	1	2	4	5	6	8
Accuracy of Position Sensing		-	+	+	+	+	+
Latency		+	+	+	+	+	+
Applied Resistance		S	+	+	+	+	+
Aesthetics		-	-	+	-	-	+
Cost of Materials		-	-	-	-	-	-
Material Strength		+	+	+	+	+	+
# of pluses		2	4	5	4	4	5
# of minuses		3	2	1	2	2	1

Concept	electrical	throttle	joystick	rps
1	hall & individual	single	ball	use existing
2	hall & individual	single	gimbal	use existing
3	hall & common	single	ball	use existing
4	hall & common	multi	gimbal	use existing
5	pot & individual	single	gimbal	use existing
6	pot & individual	multi	gimbal	use existing
7	pot & common	single	gimbal	use existing
8	pot & common	multi	gimbal	use existing

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Pugh Chart

Selection Criteria	Datum	Concepts				
	Logitech pro flight	2	4	5	6	8
Accuracy of Position Sensing		+	+	S	S	S
Latency		S	-	S	S	-
Applied Resistance		+	+	+	+	+
Aesthetics		S	+	S	S	+
Cost of Materials		-	-	+	S	S
Material Strength		-	-	-	-	-
# of pluses		2	3	2	1	2
# of minuses		2	3	1	1	2

Concept	electrical	throttle	joystick	rps
1	hall & individual	single	ball	use existing
2	hall & individual	single	gimbal	use existing
3	hall & common	single	ball	use existing
4	hall & common	multi	gimbal	use existing
5	pot & individual	single	gimbal	use existing
6	pot & individual	multi	gimbal	use existing
7	pot & common	single	gimbal	use existing
8	pot & common	multi	gimbal	use existing

William Rickles

AHP Tables Targets

[C]	Accuracy of Position Sensing	Latency	Applied Resistance	Aesthetics	Cost of Materials	Material Strength	Deviation from Given Dimensions
Accuracy of Position Sensing	1.000	1.000	5.000	3.000	3.000	7.000	9.000
Latency	1.000	1.000	3.000	3.000	1.000	5.000	5.000
Applied Resistance	0.200	0.333	1.000	1.000	1.000	5.000	7.000
Aesthetics	0.333	0.333	1.000	1.000	1.000	5.000	5.000
Cost of Materials	0.333	1.000	1.000	1.000	1.000	5.000	7.000
Material Strength	0.143	0.200	0.200	0.200	0.200	1.000	1.000
Deviation from Given Dimensions	0.111	0.200	0.143	0.200	0.143	1.000	1.000
Sum	3.121	4.067	11.343	9.400	7.343	29.000	35.000

Norm[C]	Accuracy of Position Sensing	Latency	Applied Resistance	Aesthetics	Cost of Materials	Material Strength	Deviation from Given Dimensions	Critera Weights {W}	Rank
Accuracy of Position Sensing	0.320	0.246	0.441	0.319	0.409	0.241	0.257	0.319	1
Latency	0.320	0.246	0.264	0.319	0.136	0.172	0.143	0.229	2
Applied Resistance	0.064	0.082	0.088	0.106	0.136	0.172	0.200	0.121	4
Aesthetics	0.107	0.082	0.088	0.106	0.136	0.172	0.143	0.119	5
Cost of Materials	0.107	0.246	0.088	0.106	0.136	0.172	0.200	0.151	3
Material Strength	0.046	0.049	0.018	0.021	0.027	0.034	0.029	0.032	6
Deviation from Given Dimensions	0.036	0.049	0.013	0.021	0.019	0.034	0.029	0.029	7
Sum	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	

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AHP Tables Targets

Consistency Check		
Weighted Sum Vector {Ws}	Criteria Weights {W}	Consistency Vector {Ws}./{W}
2.447	0.319	7.671
1.724	0.229	7.537
0.893	0.121	7.359
0.878	0.119	7.361
1.088	0.151	7.212
0.230	0.032	7.194
0.205	0.029	7.123
		λ= 7.351

$CI = \frac{\lambda - n}{n-1}$	$CR = \frac{CI}{RI}$	n= 7

CL= 0.058
RI=1.35
CR= 0.043

CR<0.1 :)

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AHP Tables Accuracy

[C]	2	5	8
2	1.00	5.00	5.00
5	0.20	1.00	1.00
8	0.20	1.00	1.00
Sum	1.40	7.00	7.00

Norm[C]	2	5	8	Criteria Weights {W}	
2	0.714	0.714	0.714	0.714	1
5	0.143	0.143	0.143	0.143	2
8	0.143	0.143	0.143	0.143	2
Sum	1.000	1.000	1.000	1.000	

CI= 0
RI= 0.52
CR= 0

0 <0.1

Consistency Check		
Weighted Sum Vector {Ws}	Weights {W}	Consistency Vector {Ws}./{W}
2.14	0.71	3.00
0.43	0.14	3.00
0.43	0.14	3.00
		λ= 3.00

$CI=\frac{\lambda-n}{n-1}$	$CR=\frac{CI}{RI}$	n= 3

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AHP Tables Latency

[C]	2	5	8
2	1.00	0.33	7.00
5	3.00	1.00	7.00
8	0.14	0.14	1.00
Sum	4.14	1.48	15.00

Norm[C]	2	5	8	{W}
2	0.241	0.226	0.467	0.311
5	0.724	0.677	0.467	0.623
8	0.034	0.097	0.067	0.066
Sum	1.000	1.000	1.000	1.000

Consistency Check		
{Ws}	{W}	{Ws}./{W}
0.981	0.311	3.150
2.018	0.623	3.241
0.199	0.066	3.022
	λ=	3.138

CI=	0.069019
RI=	0.52
CR=	0.132728

$CI = \frac{\lambda - n}{n-1}$	$CR = \frac{CI}{RI}$	n= 3

Francisco Lopez

AHP Tables Cost of Materials

[C]	2	5	8
2	1.00	0.14	0.20
5	7.00	1.00	3.00
8	5.00	0.33	1.00
Sum	13.00	1.48	4.20

Norm[C]	2	5	8	{W}
2	0.077	0.097	0.048	0.074
5	0.538	0.677	0.714	0.643
8	0.385	0.226	0.238	0.283
Sum	1.000	1.000	1.000	1.000

Check		
{Ws}	{W}	{Ws}./{W}
0.222	0.074	3.013
2.008	0.643	3.121
0.866	0.283	3.062
	λ=	3.066

CI=	0.032756
RI=	0.52
CR=	0.062992

0.06<0.1 :)

$CI = \frac{\lambda - n}{n-1}$	$CR = \frac{CI}{RI}$	n= 3

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AHP

AHP for the targets resulted in the following data

Criteria	{W}	Rank
Accuracy of Position Sensing	0.319	1
Latency	0.229	2
Applied Resistance	0.121	4
Aesthetics	0.119	5
Cost of Materials	0.151	3
Material Strength	0.032	6
Deviation from Given Dimensions	0.029	7

CR=0.043

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AHP

Accuracy of position sensing AHP

Concept	{W}	Rank
2	0.71	1
5	0.14	2
8	0.14	2

CR=0

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AHP

Latency AHP

Concept	{W}	Rank
2	0.311	2
5	0.623	1
8	0.066	3

CR=0.133

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AHP

Cost of Materials AHP

[C]	{W}	Rank
2	0.074	3
5	0.643	1
8	0.283	2

CR=0.063

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