Weightless Integrated Instrument for Ground-based Laboratory Sensing

Critical Design Review

December 07, 2022

ASEN 4018 – 012, Team 11

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Presentation Outline

1. Project Purpose and Objectives
2. Design Solution
3. Critical Project Elements & Risks
4. Design Requirements & Satisfaction
5. Verification & Validation
6. Project Planning
7. Appendix

Project Overview

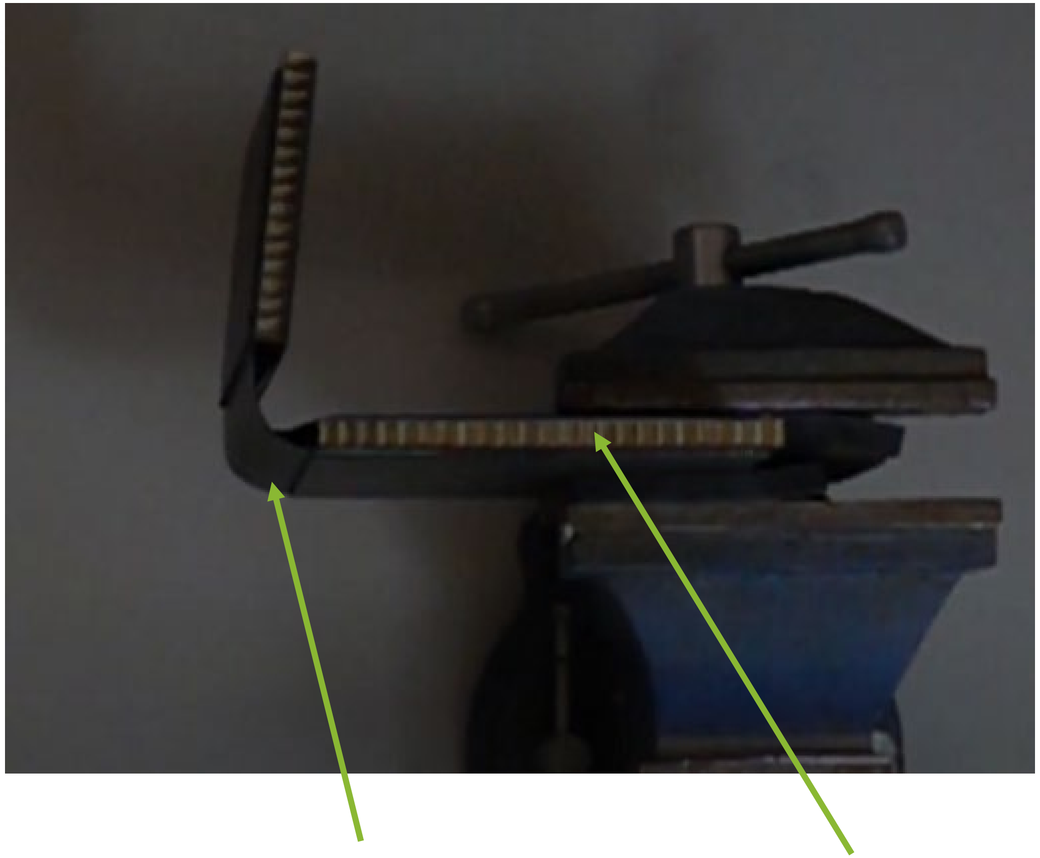
WIIGLS

Mission Statement

Our mission is to create a modular **W**eightless **I**ntegrated **I**nstrument for **G**round-based **L**aboratory **S**ensing (WIIGLS) to characterize the motion of a deployable panel structure.

Baseline Hinge-Panel System

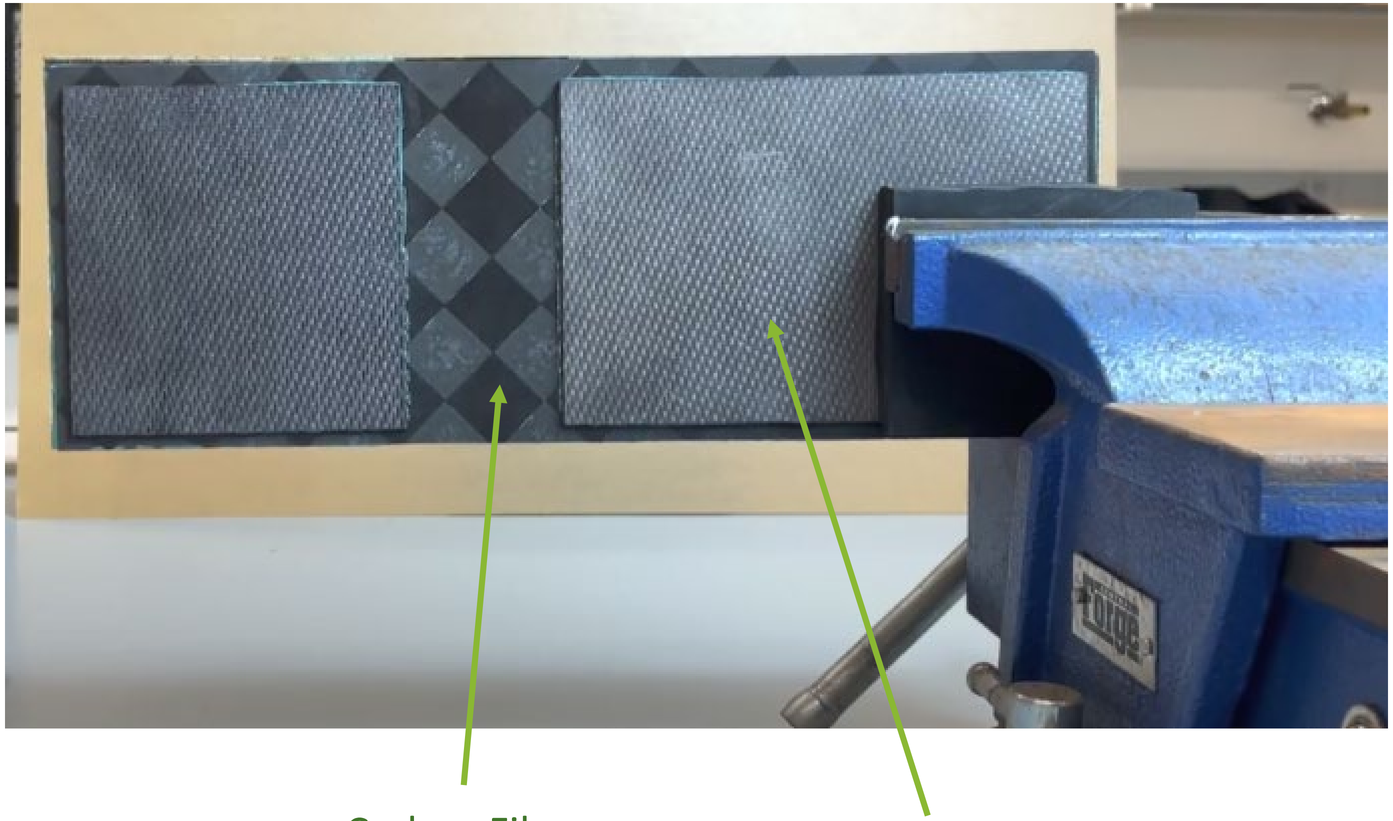
Top View



Carbon Fiber Hinge

Honeycomb Paneling

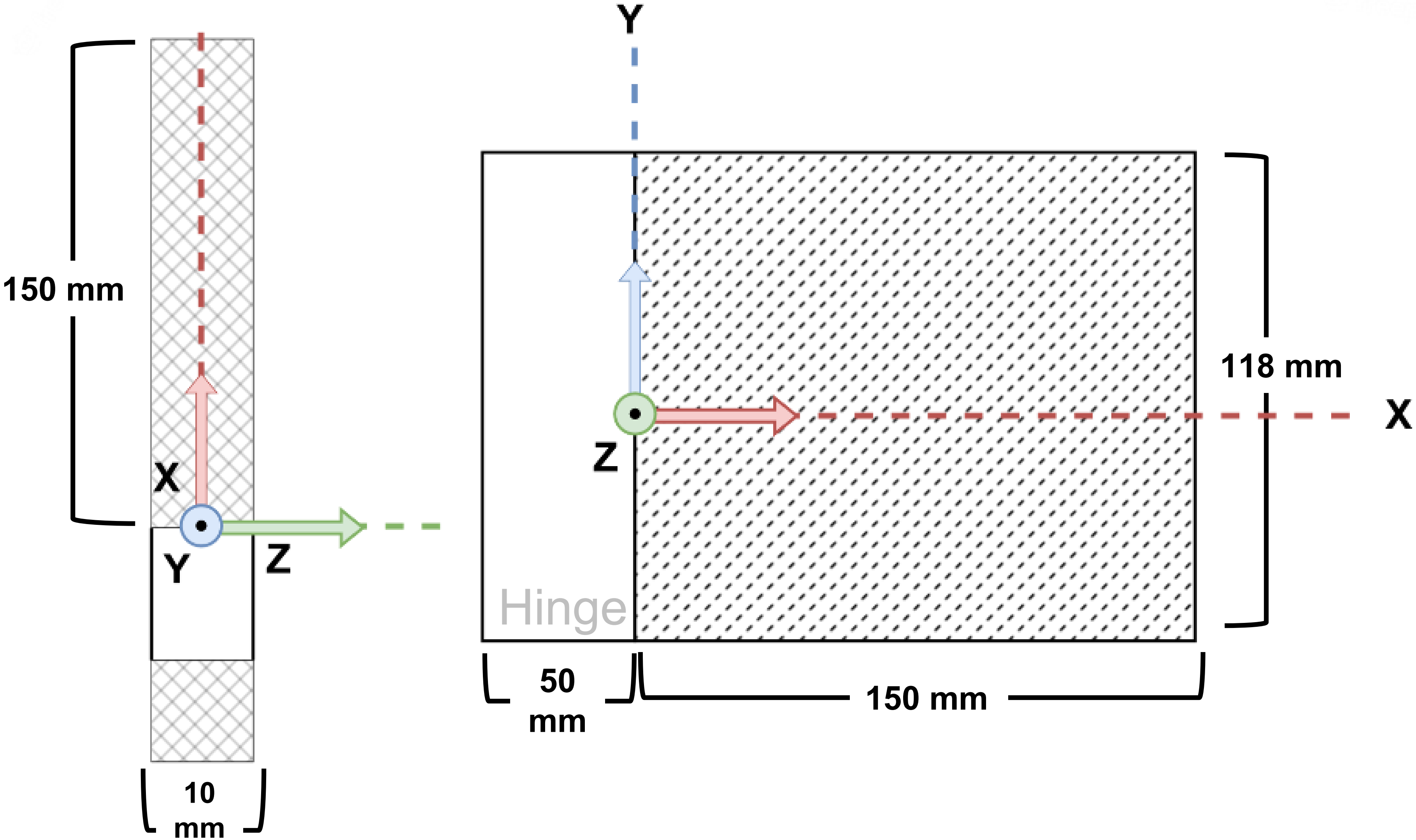
Side View



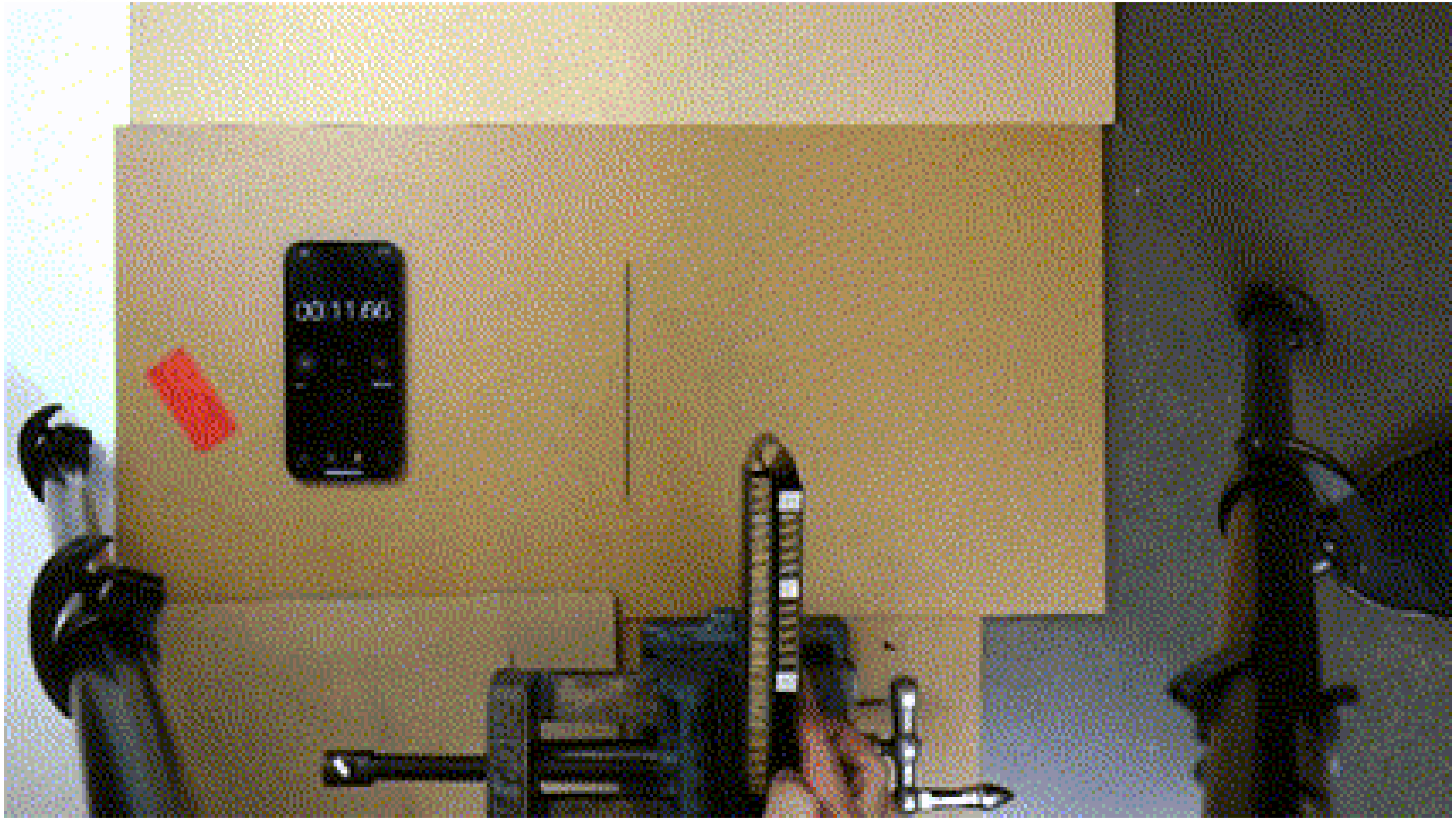
Carbon Fiber Hinge

Carbon Fiber Reinforcement

Coordinate References



Deployment



Problem Statement

Problem

- Dynamics of the panel and vibrational modes are largely unknown
- Must understand maximum expected accelerations and frequencies
- Must be tailored to specific range of sensing conditions

Goals

- Design a sensor suite that can accurately capture all panel motion
- Construct a modified panel to integrate sensor suite
- Verify and data against our models

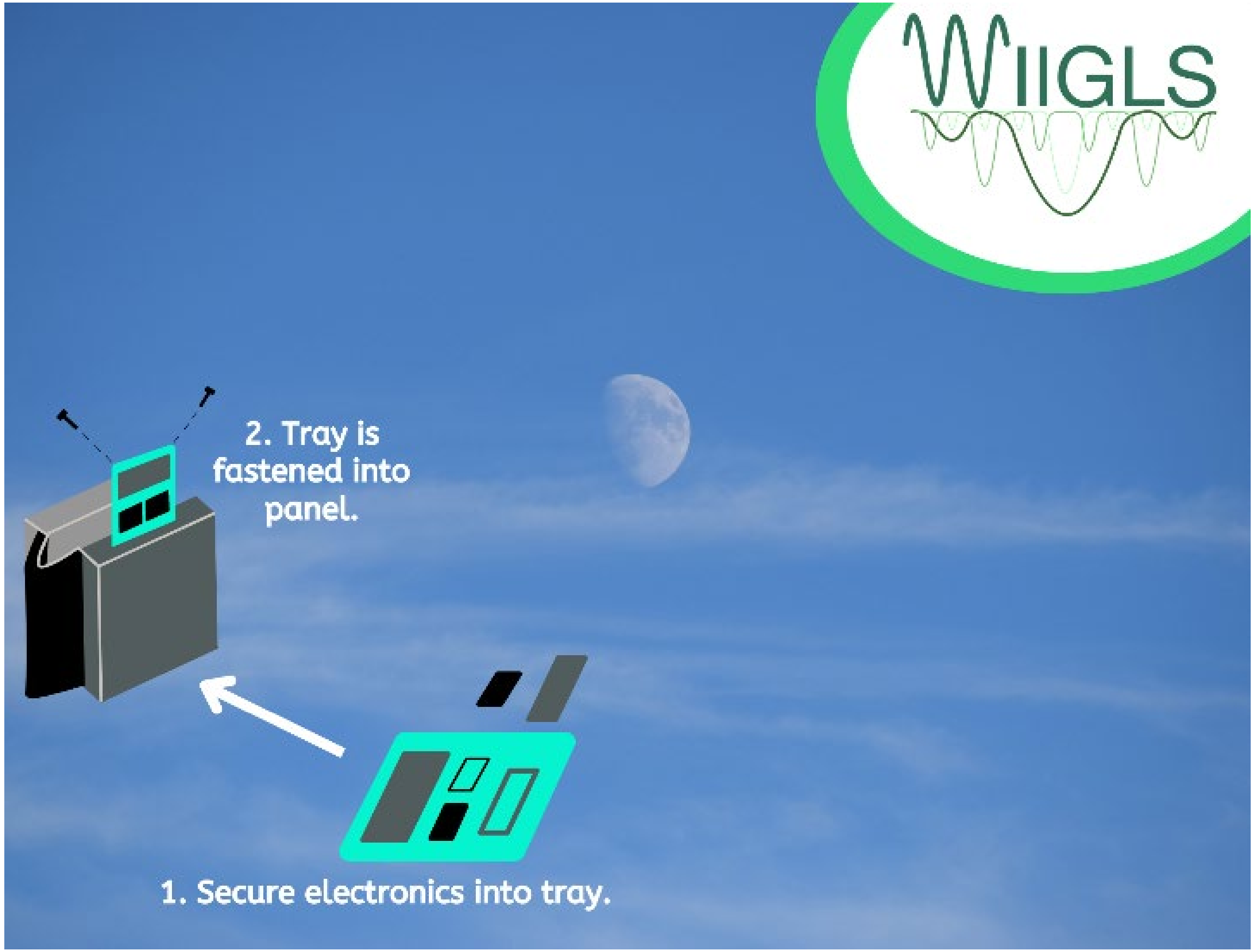
Project Scope

- **Estimate & Predict** the motion of the panel
- **Select** sensors to record predicted motion
- **Create** sensor tray to securely fit within the panel
- **Manufacture** a modified panel
- **Conduct** ground-based modified panel deployment test
- **Collect & Analyze** data to deliver to the customer

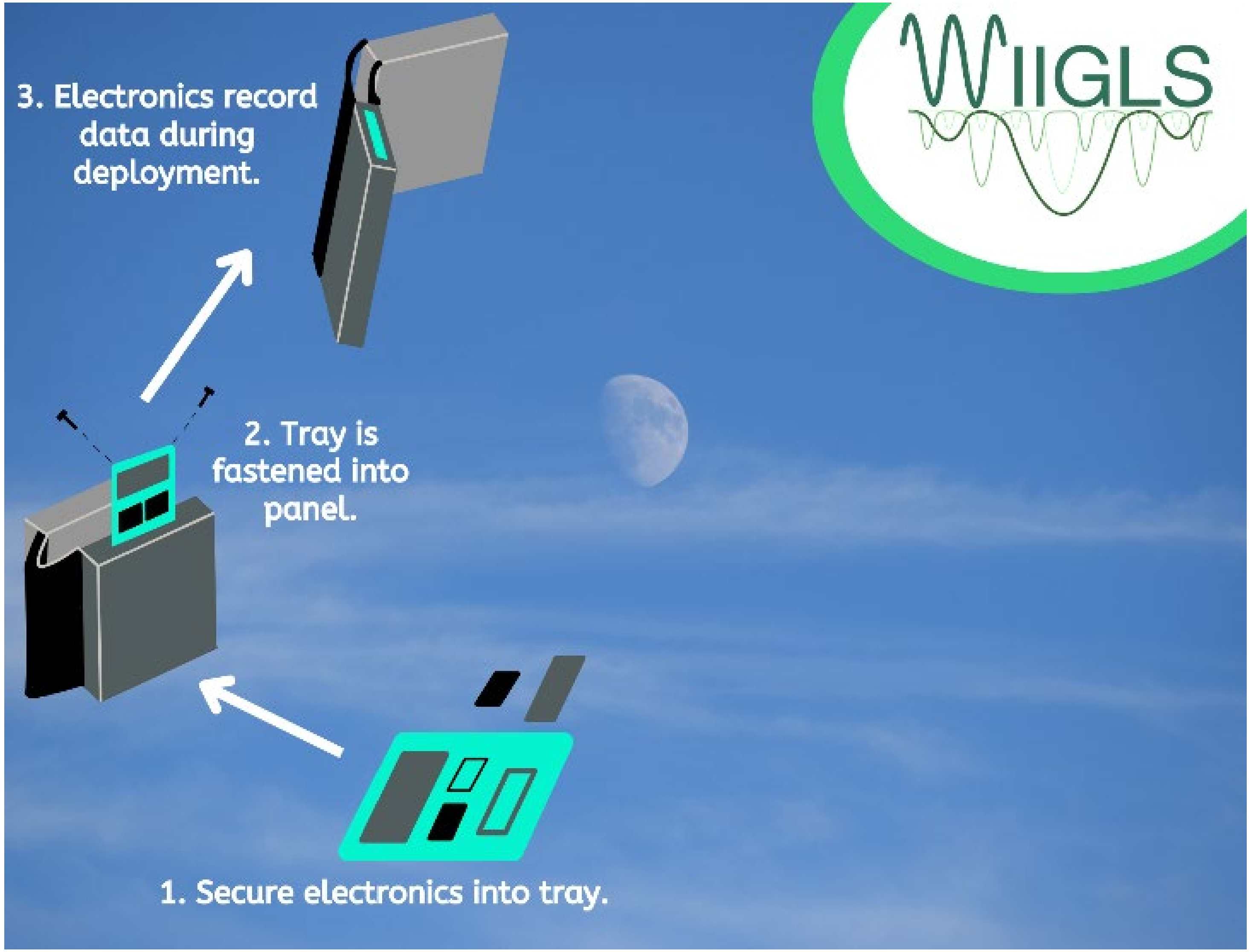
Concept of Operations: Project Level

1. Secure electronics into tray.

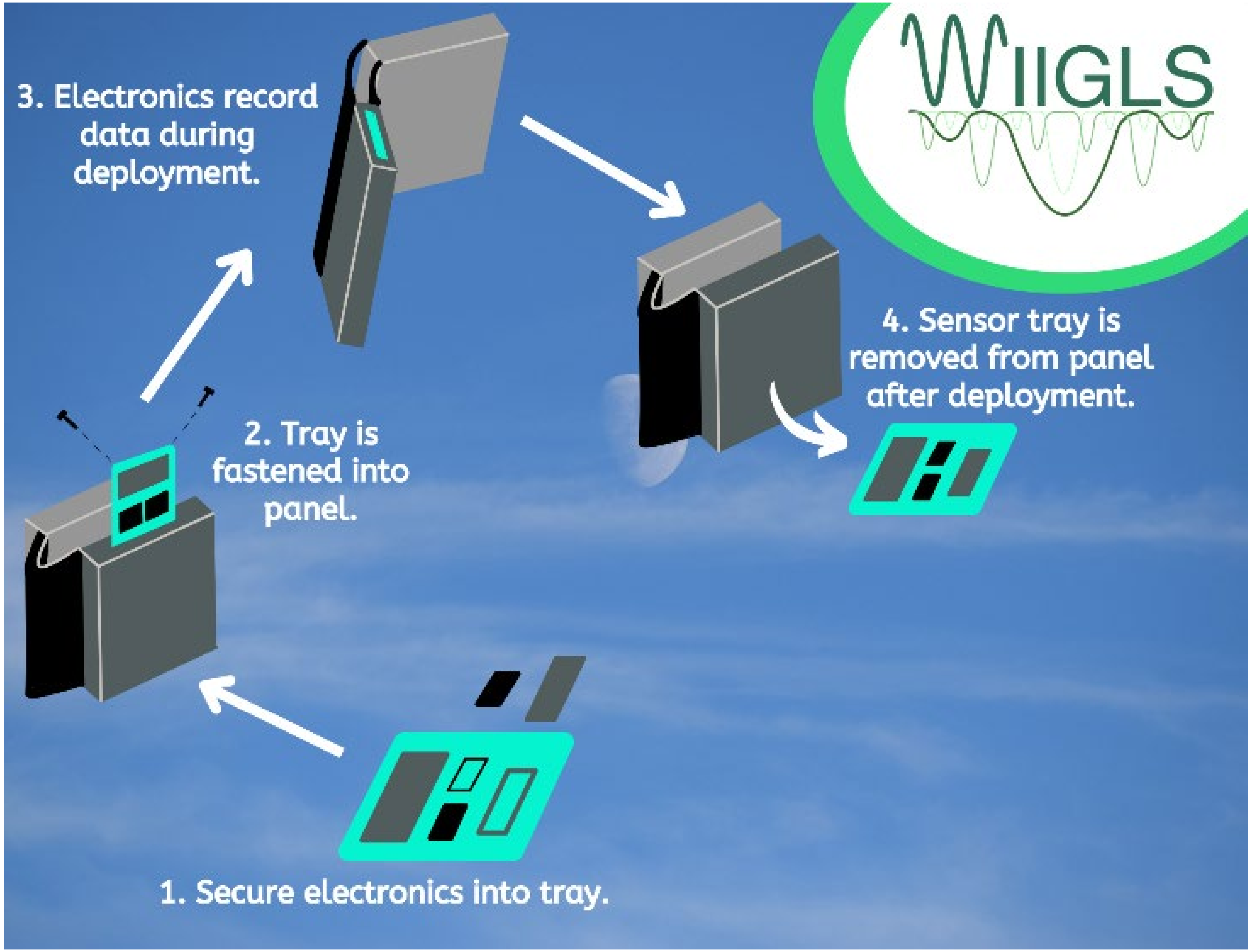
Concept of Operations: Project Level



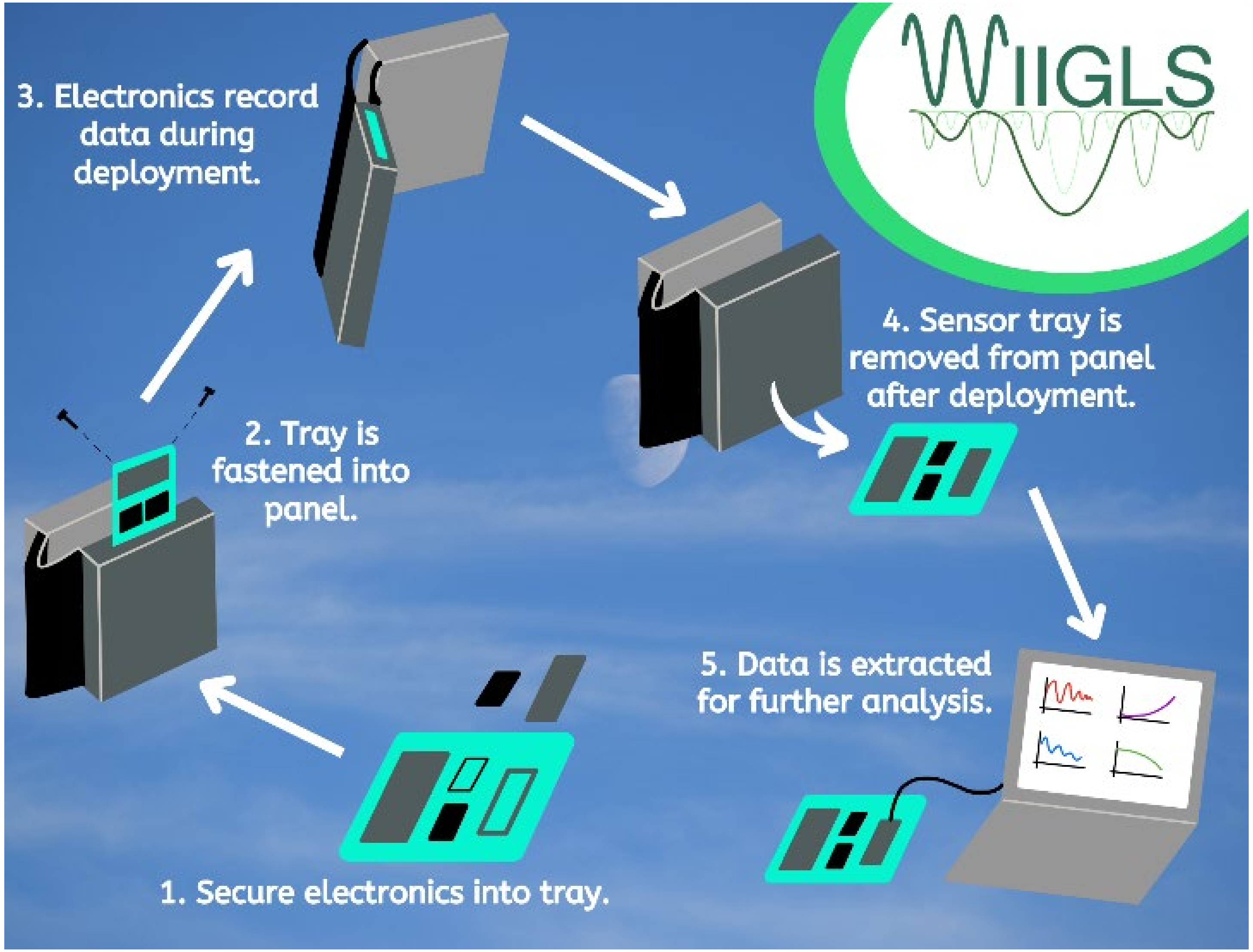
Concept of Operations: Project Level



Concept of Operations: Project Level



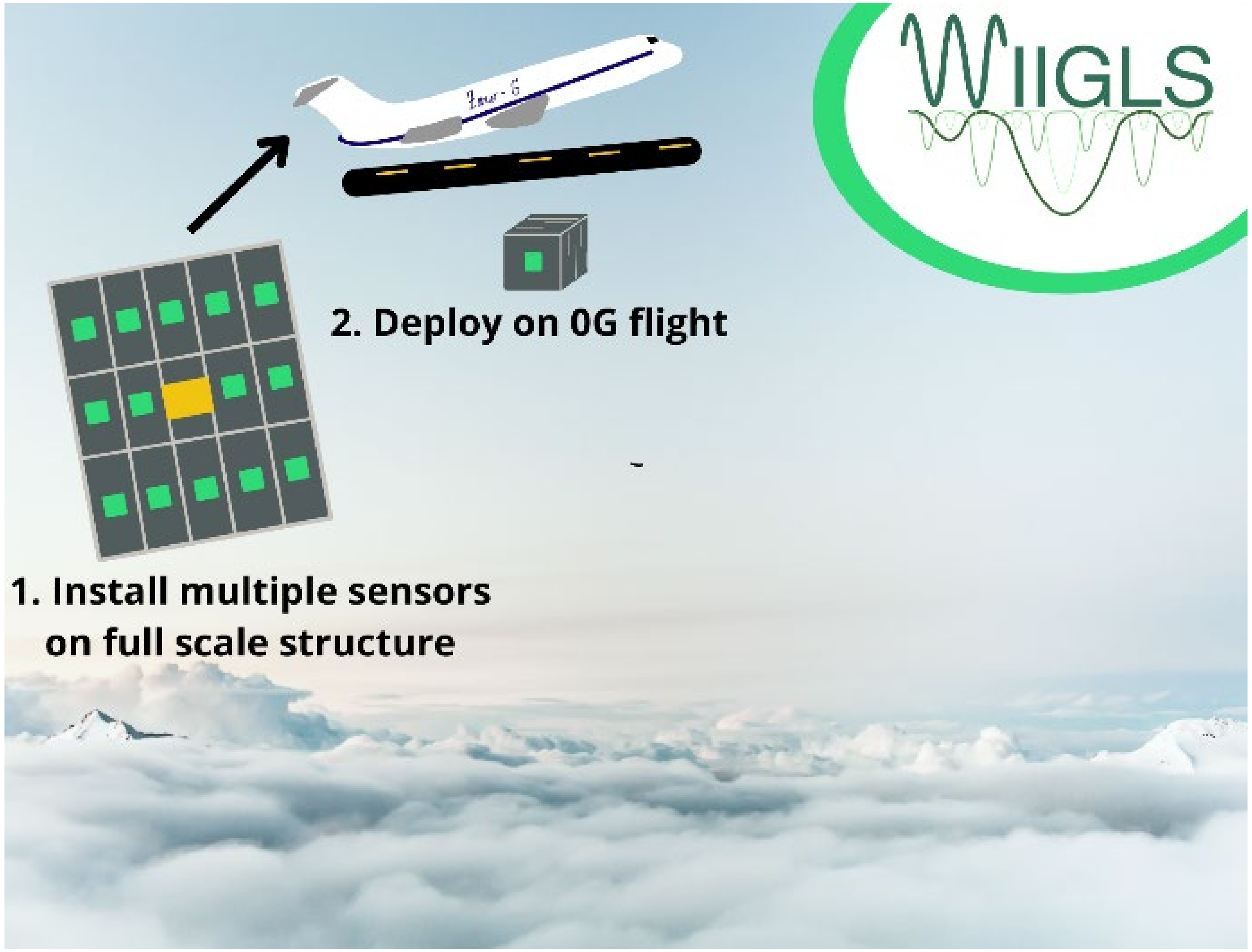
Concept of Operations: Project Level



Concept of Operations: Mission Level

1. Install multiple sensors on full scale structure

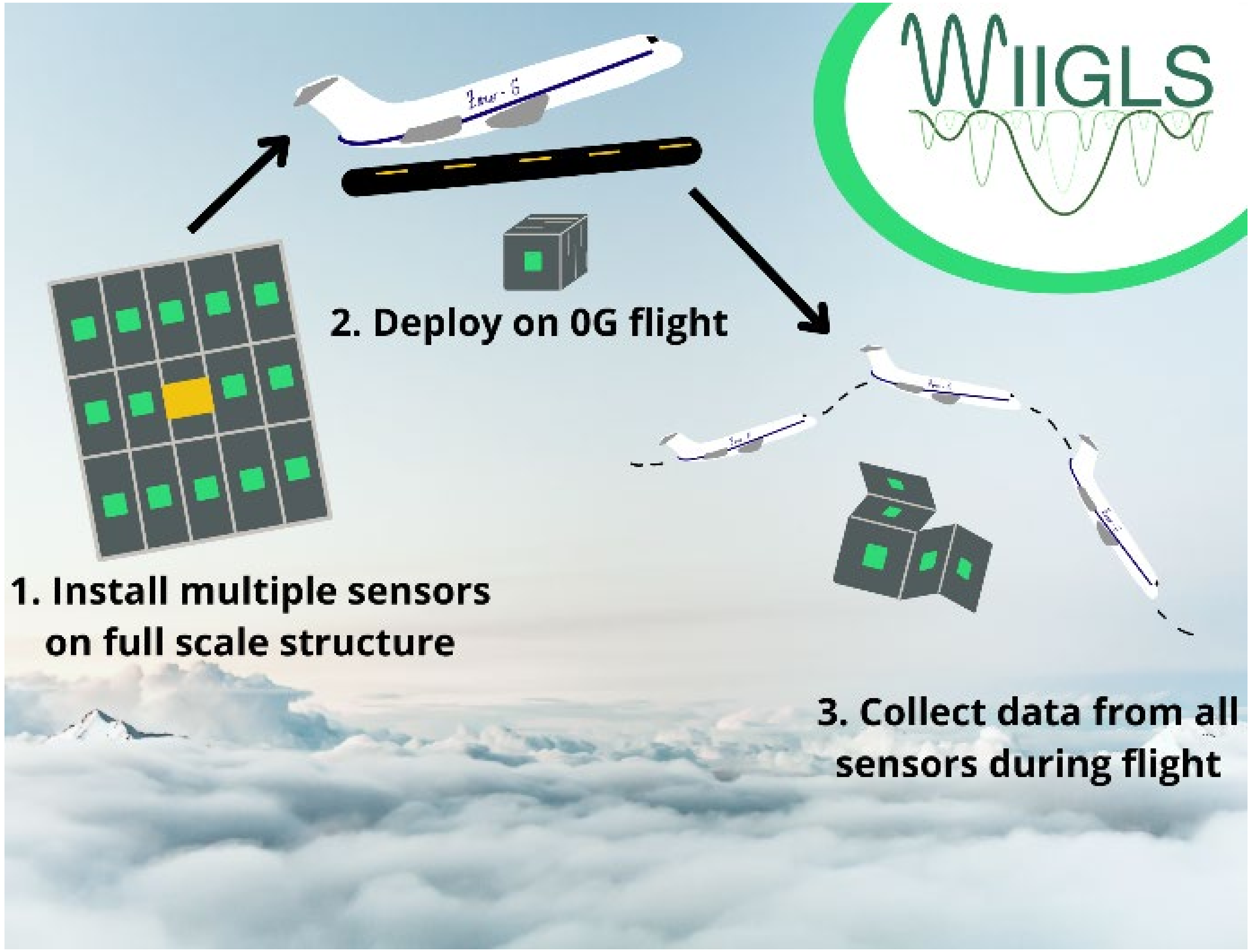
Concept of Operations: Mission Level



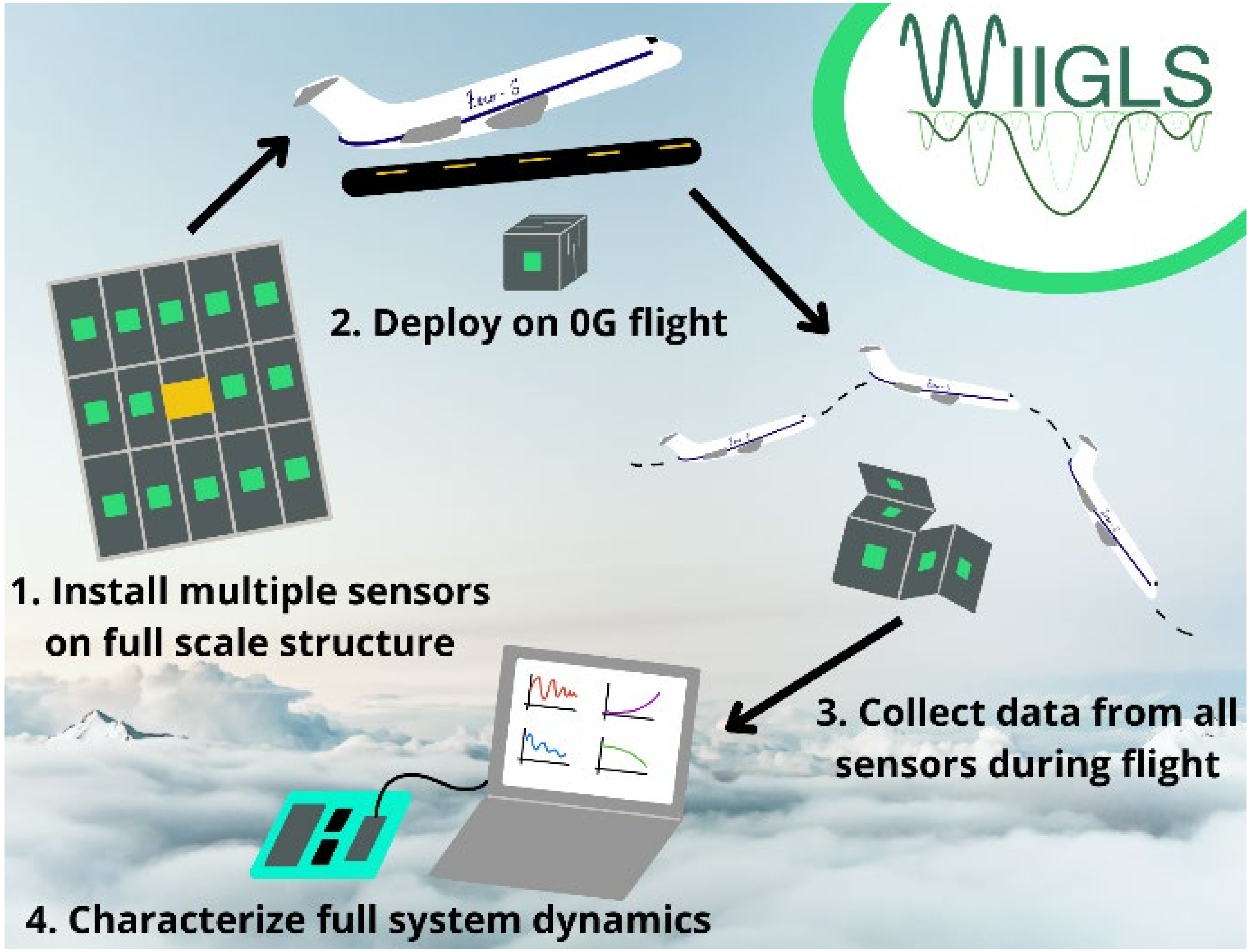
2. Deploy on 0G flight

1. Install multiple sensors on full scale structure

Concept of Operations: Mission Level



Concept of Operations: Mission Level



1. Install multiple sensors on full scale structure

2. Deploy on 0G flight

3. Collect data from all sensors during flight

4. Characterize full system dynamics

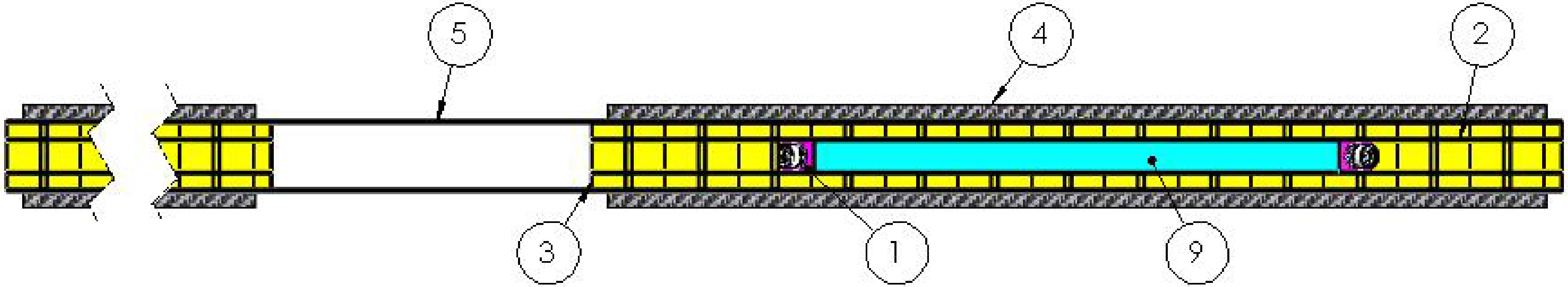
Design Solution

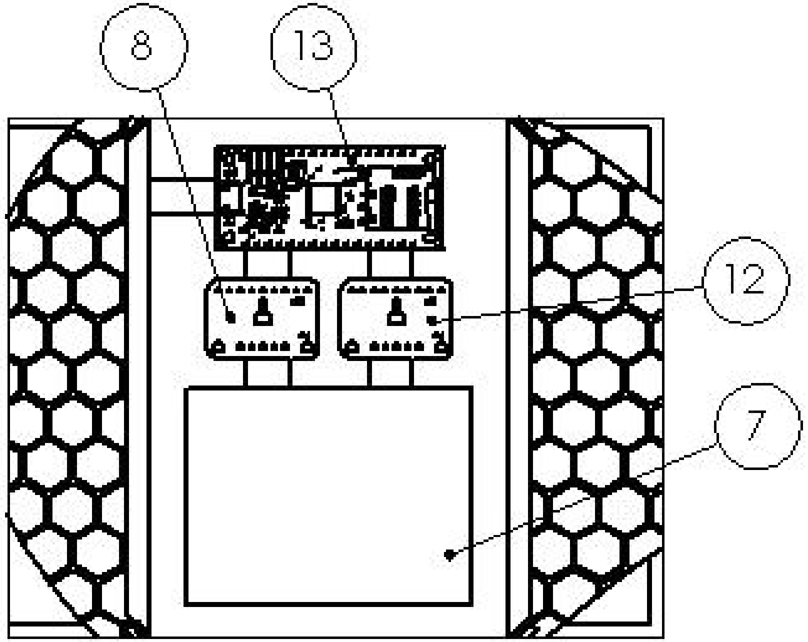
Alex Bergemann

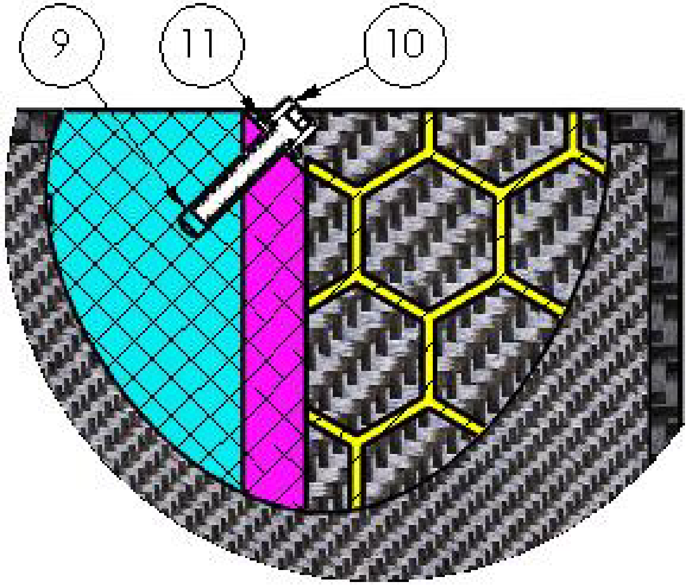
Complete CAD Model

Assembly Process

Bill of Materials

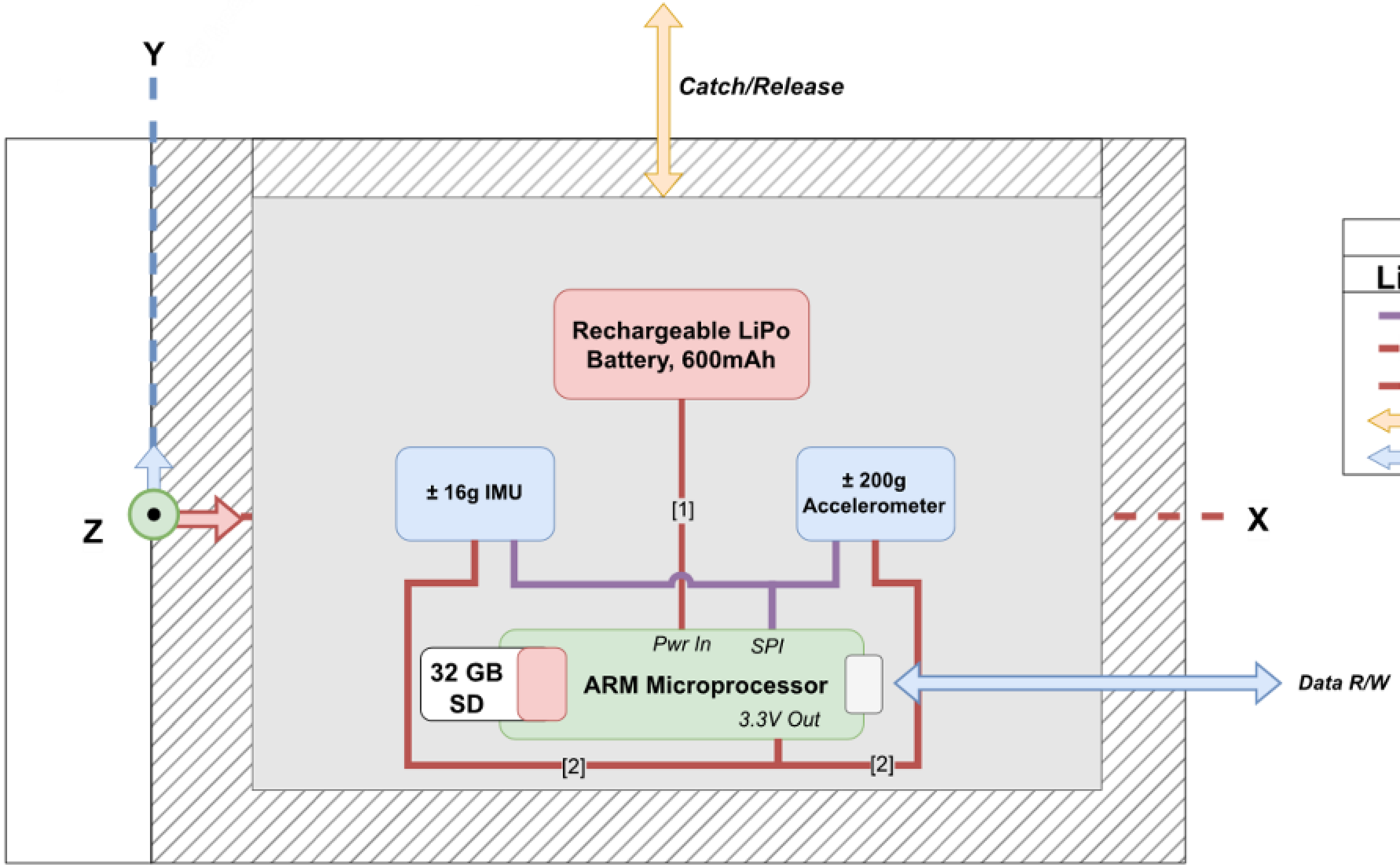






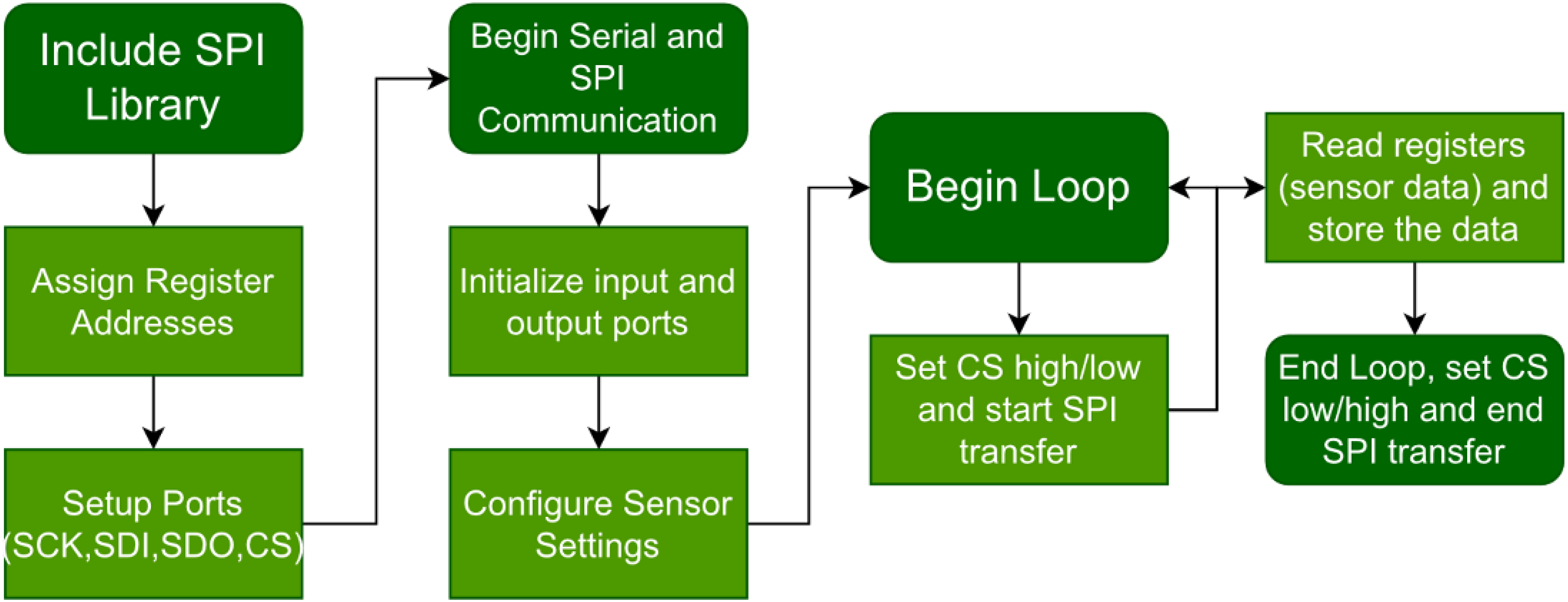
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Guide Rails	Aluminum 6061	2
2	Carbon Fiber Sheet	Lightweight Carbon Fiber Sheet (0.2 mm thick)	4
3	Honeycomb	Nomex	4
4	8181K231	Ultra-Strength Lightweight Carbon Fiber Reinforcement	4
5	1824N11	Hinge Carbon Fiber (0.3 mm thick)	2
9	Delrin 100AF	Sensor Tray	1
7	LP204965	Rechargable LiPo Battery	1
8	ADXL375	3 DOF Accelerometer	1
9	91732A204	18-8 Stainless Steel Helical Insert	1
10	91864A005	Black-Oxide Alloy Steel Socket Head Screw	4
11	92146A520	18-8 Stainless Steel Split Lock Washer	4
12	LM6DSOX	6 DOF IMU	1
13	Featherboard	Mircoprocessor	1

Functional Block Diagram



Link Definitions	
Link	**Description**
━	SPI - 2 MHz Clock
━[1]━	Power - Unregulated
━[2]━	Power - 3.3V Regulated
⇔	Fastener Connection
⇔	USB Data Transfer

Software Functional Block Diagram



Include SPI Library

Assign Register Addresses

Setup Ports (SCK,SDI,SDO,CS)

Begin Serial and SPI Communication

Initialize input and output ports

Configure Sensor Settings

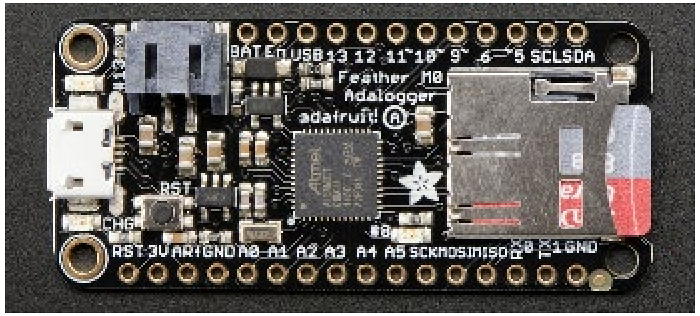
Begin Loop

Set CS high/low and start SPI transfer

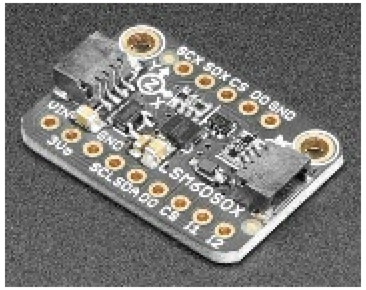
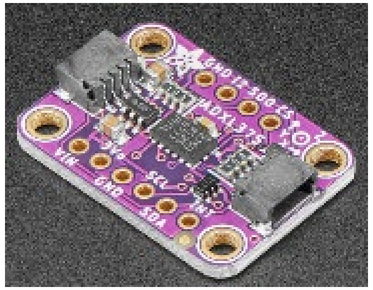
Read registers (sensor data) and store the data

End Loop, set CS low/high and end SPI transfer

Sensing Component Summary

Adafruit Featherlogger M0	
Clock	48 MHz (maximum)
Current	6.3 mA
	

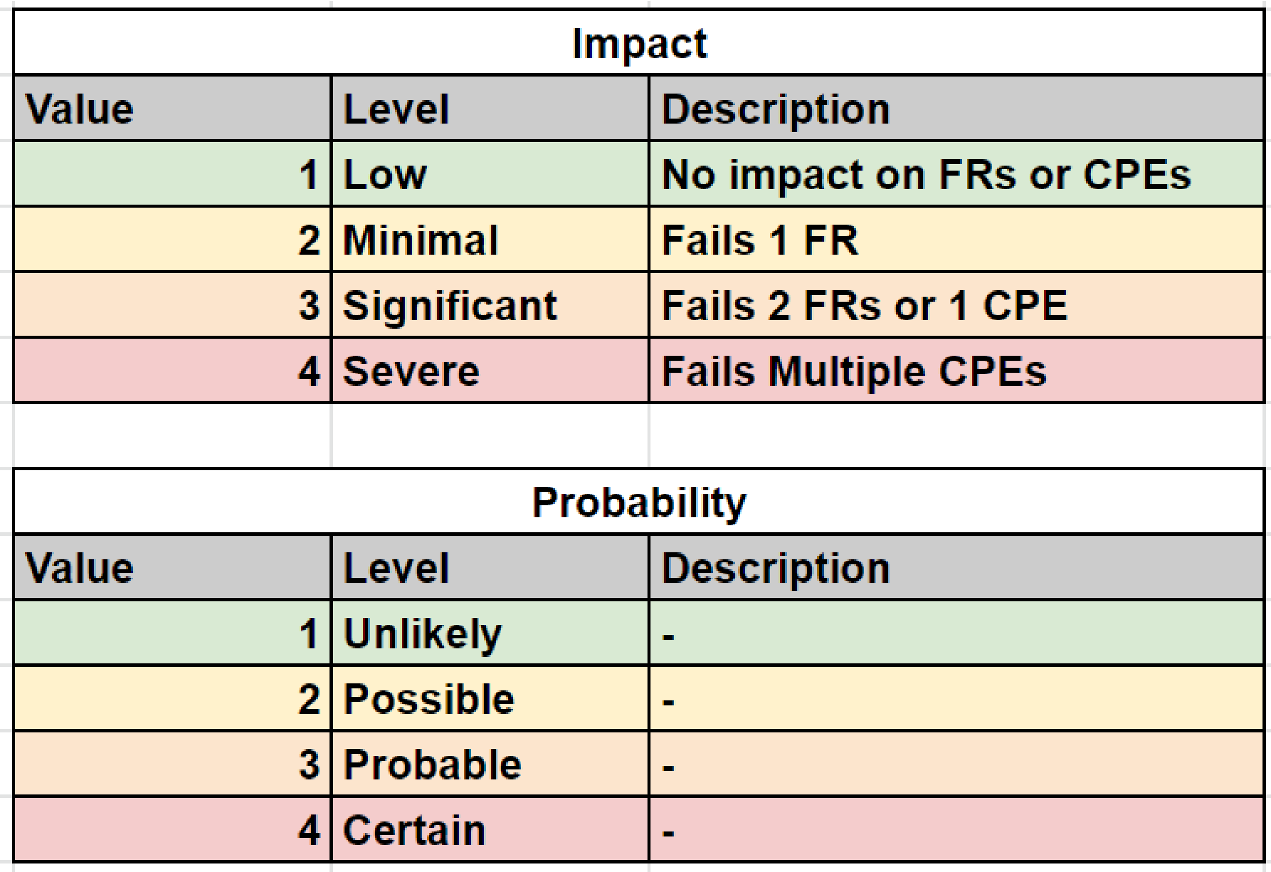
Battery	
Capacity	600 mAh
Chemistry	LiPo 1C
	

Sensors		
	LM6DSOX IMU	**ADXL375 Accel**
Range [G]	±16G	± 200G
ODR [Hz]	6666	800
Current [mA]	0.55	0.14
		

Critical Project Elements & Risks

Céu Gomez

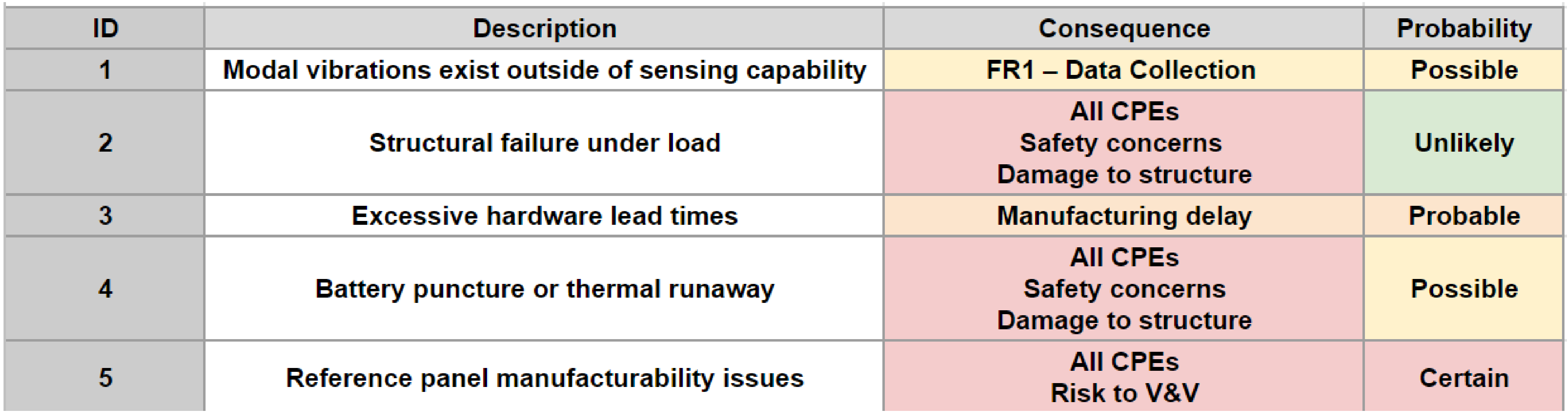
Risks Scoring Definitions



Impact		
Value	Level	Description
1	Low	No impact on FRs or CPEs
2	Minimal	Fails 1 FR
3	Significant	Fails 2 FRs or 1 CPE
4	Severe	Fails Multiple CPEs

Probability		
Value	Level	Description
1	Unlikely	-
2	Possible	-
3	Probable	-
4	Certain	-

Risks

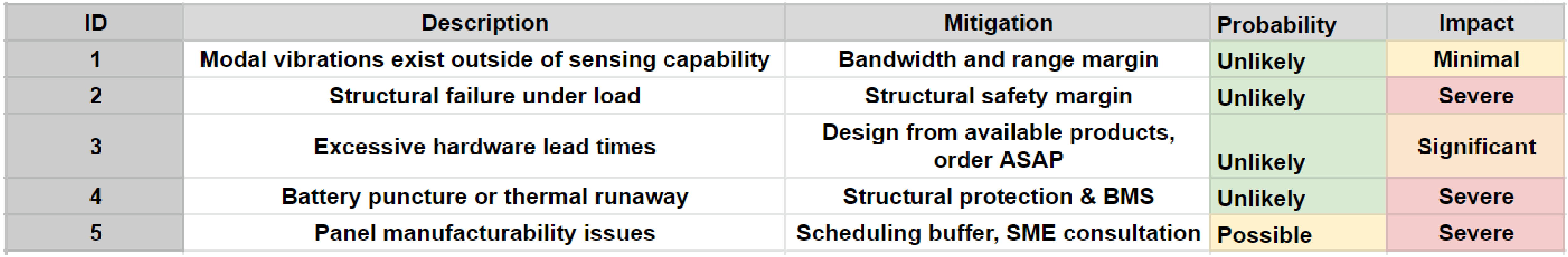


ID	Description	Consequence	Probability
1	Modal vibrations exist outside of sensing capability	FR1 – Data Collection	Possible
2	Structural failure under load	All CPEs Safety concerns Damage to structure	Unlikely
3	Excessive hardware lead times	Manufacturing delay	Probable
4	Battery puncture or thermal runaway	All CPEs Safety concerns Damage to structure	Possible
5	Reference panel manufacturability issues	All CPEs Risk to V&V	Certain

Risk Matrix

		Impact			
Probability	-	Low	Minimal	Significant	Severe
	Certain				5
	Probable			3	
	Possible		1		4
	Unlikely				2

Mitigation Strategies



ID	Description	Mitigation	Probability	Impact
1	Modal vibrations exist outside of sensing capability	Bandwidth and range margin	Unlikely	Minimal
2	Structural failure under load	Structural safety margin	Unlikely	Severe
3	Excessive hardware lead times	Design from available products, order ASAP	Unlikely	Significant
4	Battery puncture or thermal runaway	Structural protection & BMS	Unlikely	Severe
5	Panel manufacturability issues	Scheduling buffer, SME consultation	Possible	Severe

Post Mitigation

		Impact			
Probability	-	Low	Minimal	Significant	Severe
	Certain				
	Probable				
	Possible				5
	Unlikely		1	3	4 2

Design Requirements & Satisfaction

Gerry Romero, Anabel de Montebello, and Céu Gomez

Derived Design Requirements

Desired Results

Panel Acceleration

Panel Frequency

?

↓

Resulting DR's

Necessary acceleration sensing range

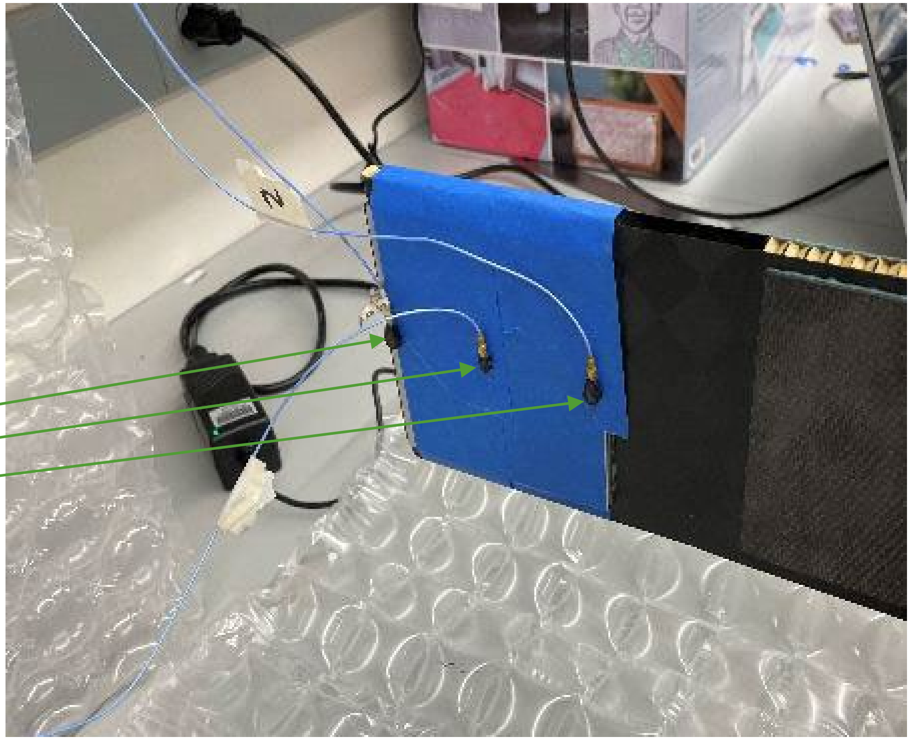
Necessary sensing frequency range

✓

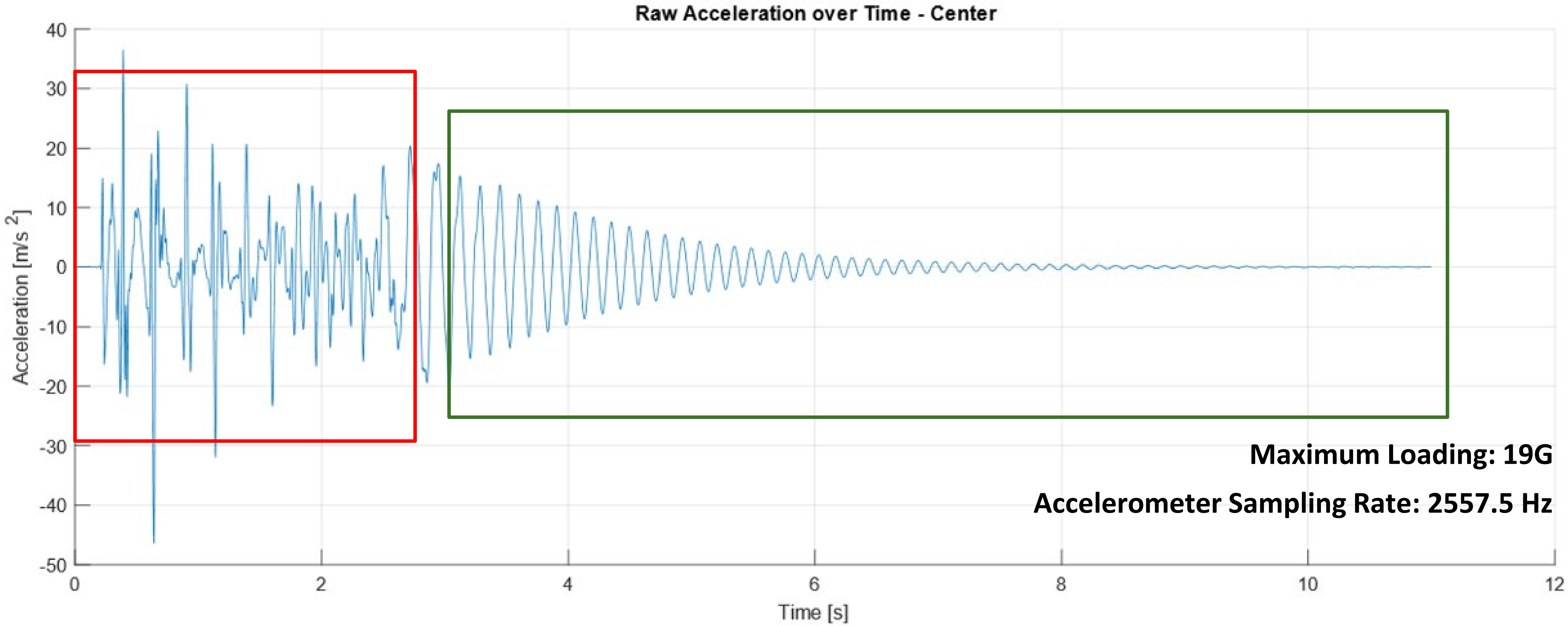
Teardrop Accelerometers

- Record accelerations over the panel
- Predict experienced forces and frequencies
- Max G-load: 19 G

Model# 352C22
9.55 mV/g
±500 g pk
1-10,000 Hz
4 tests conducted:
Unmodified panel
Panel + 60 grams
Panel + 120 grams
Panel + 180 grams



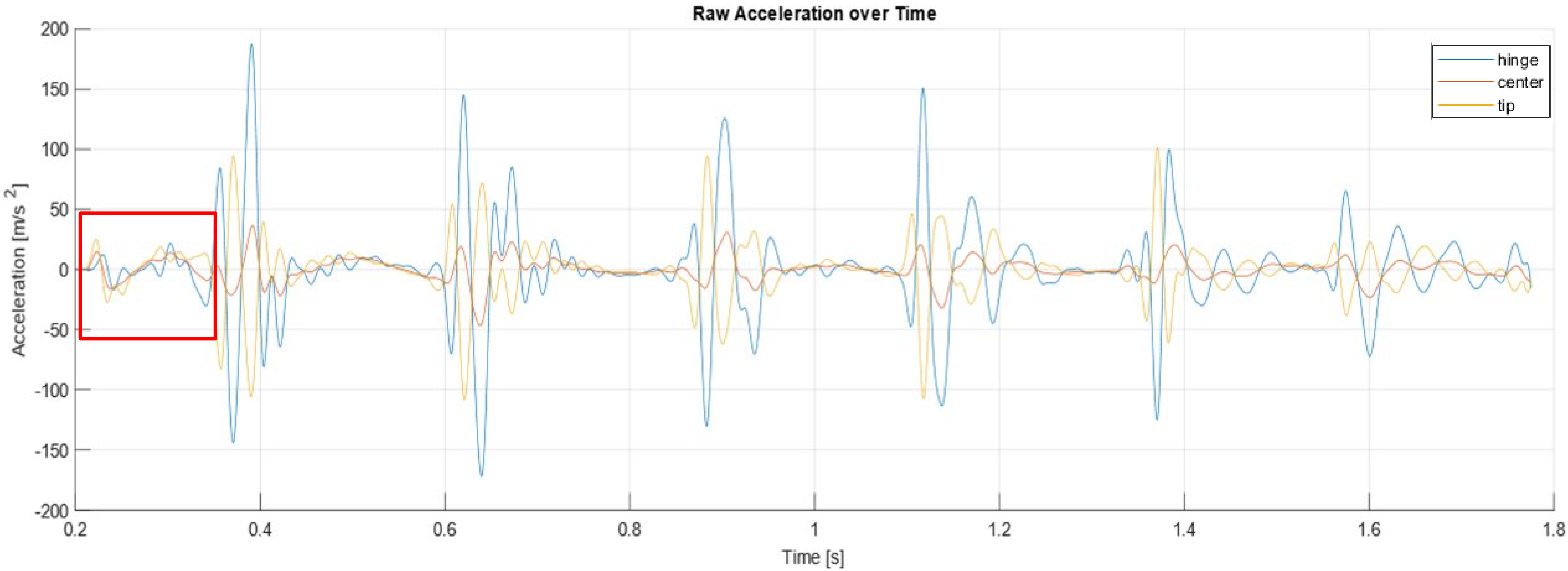
Teardrop Accelerometer Testing – Rise



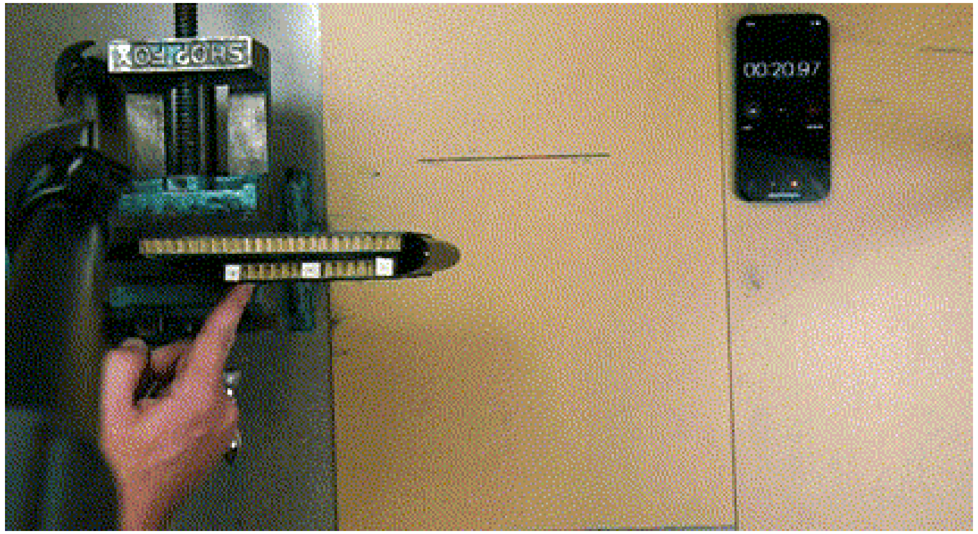
Maximum Loading: 19G

Accelerometer Sampling Rate: 2557.5 Hz

Teardrop Accelerometer Testing

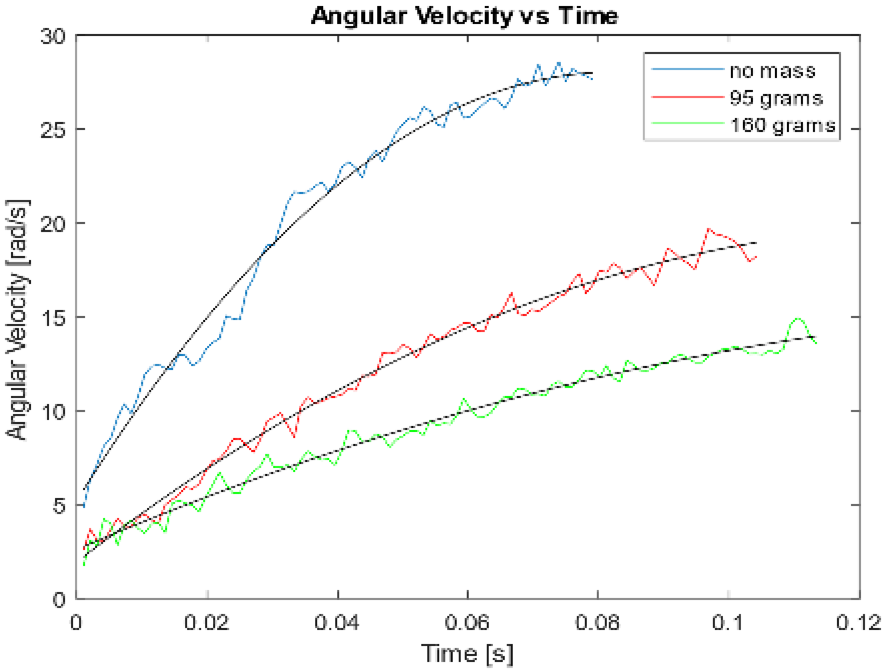


1-Dimensional Model



(Optically Tracked)

ω

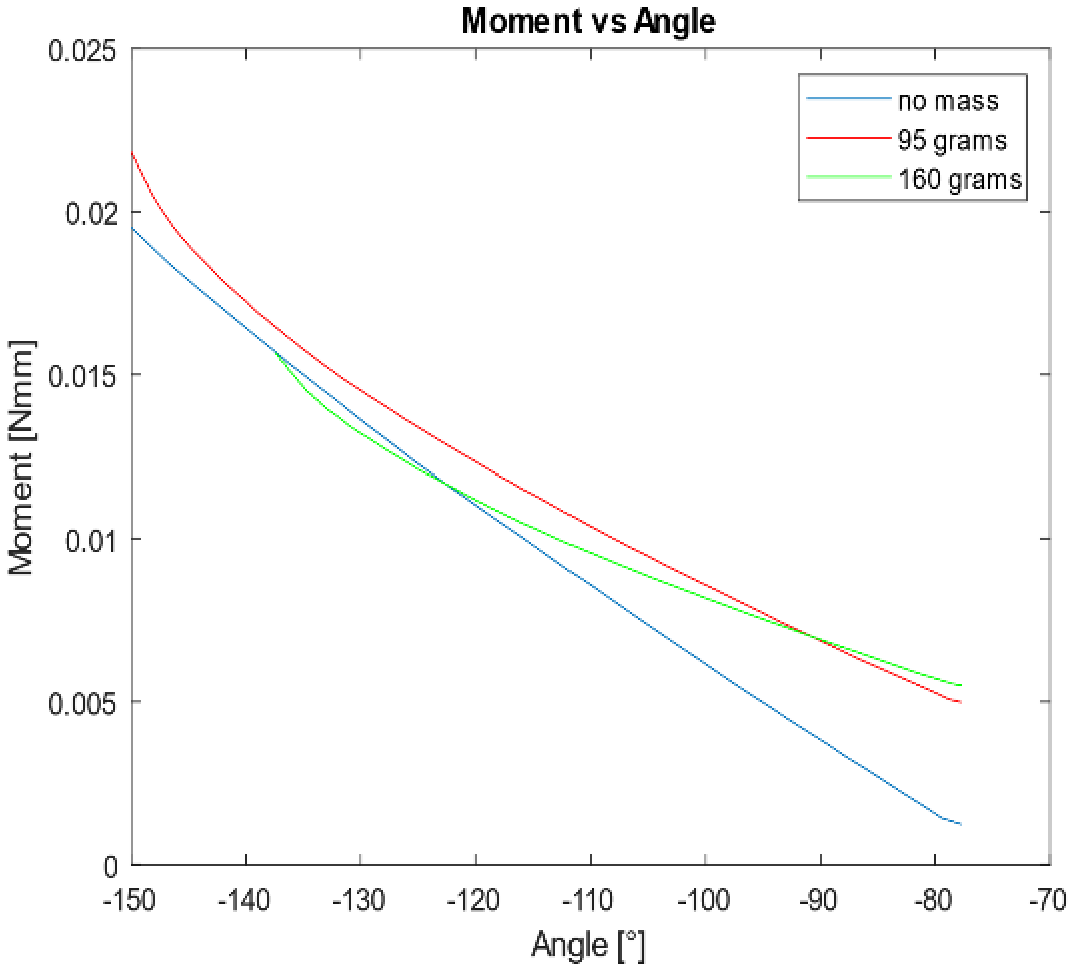


$$I=\frac{1}{3}mL^2$$

$d\omega/dt$

$$M=I\alpha$$

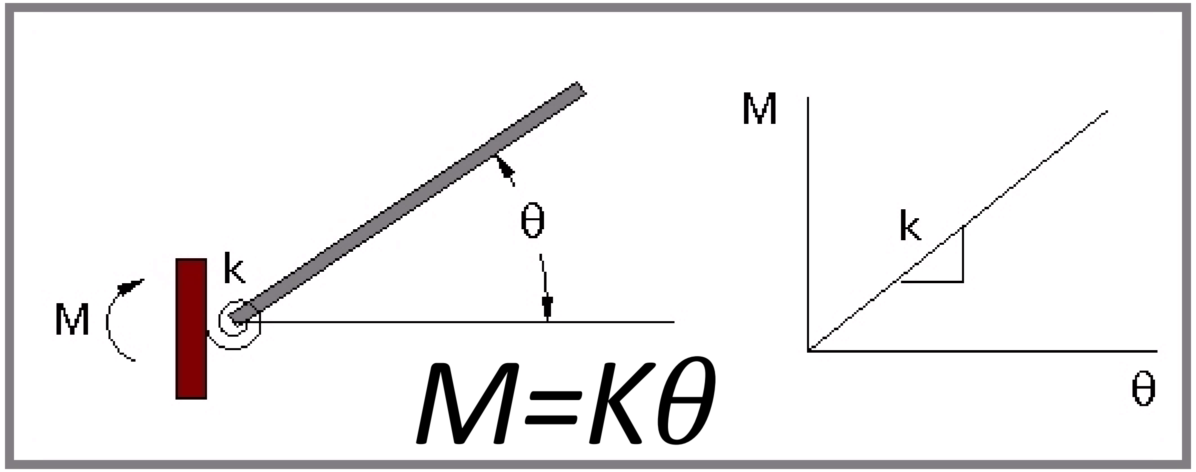
1-Dimensional Model



K = -.0169 Nmm/rad

K = -.0131 Nmm/rad

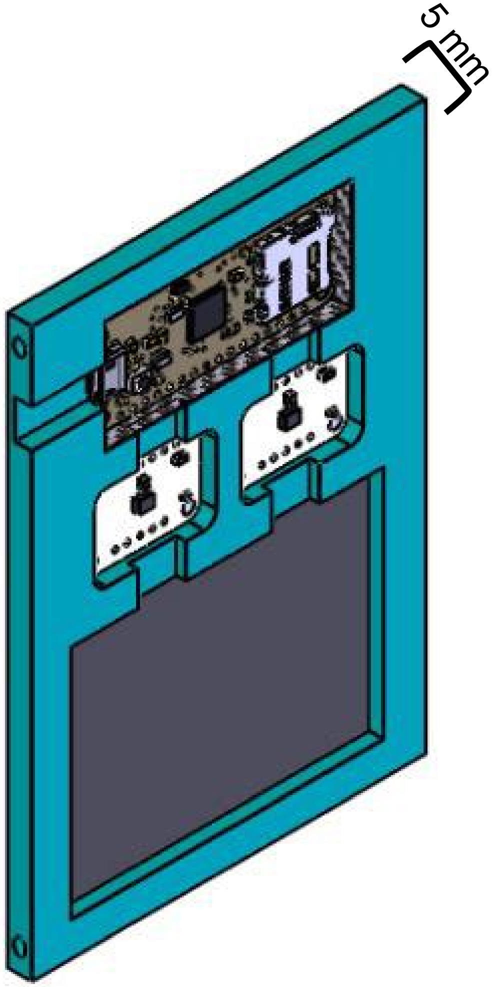
K = -.0094 Nmm/rad

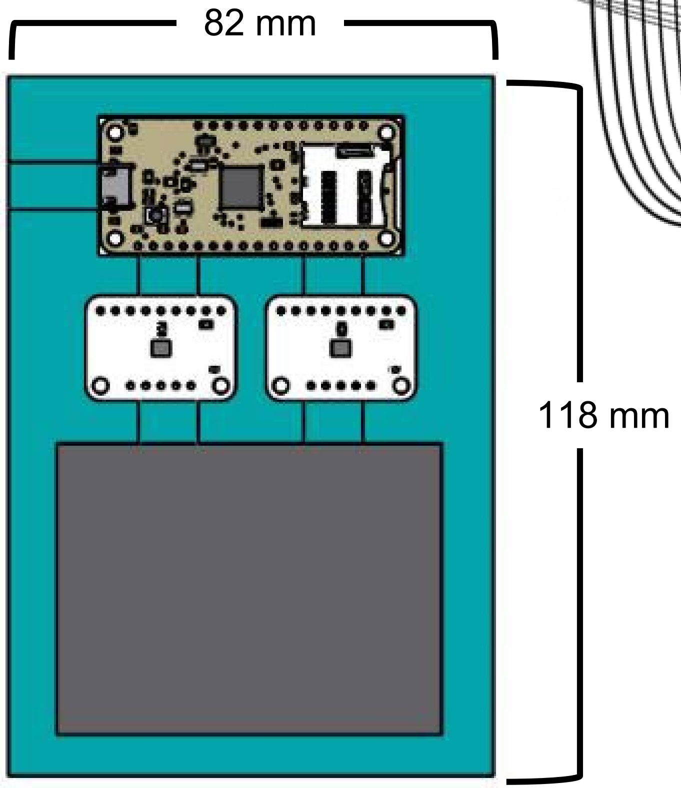


$$M=K\theta$$

Sensor Tray Design

- Material selection
  - Delrin
    - Density: 1.54 g/cm^3
    - Youngs Modulus: 3 GPa
    - DuPont Engineering
- Sensor interface
  - Epoxied into slide-fit cutouts
  - Cyanoacrylate
    - Shear strength: 15 MPa
    - Tensile strength: 26 MPa
    - Loctite Corporation





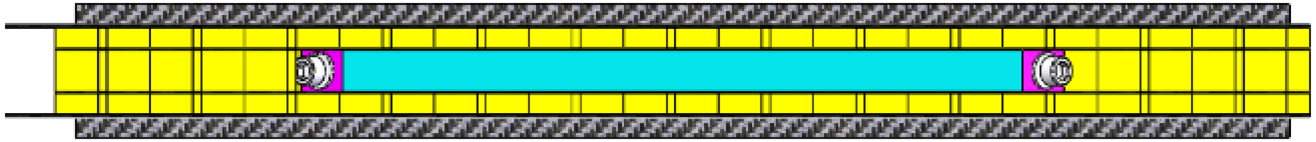
DR2.1 - 200 x 150 x 5 mm ✓

DR3.1 - Minimize sensor mount noise ✓

DR2.3 - Known MOI ✓

Panel Modifications

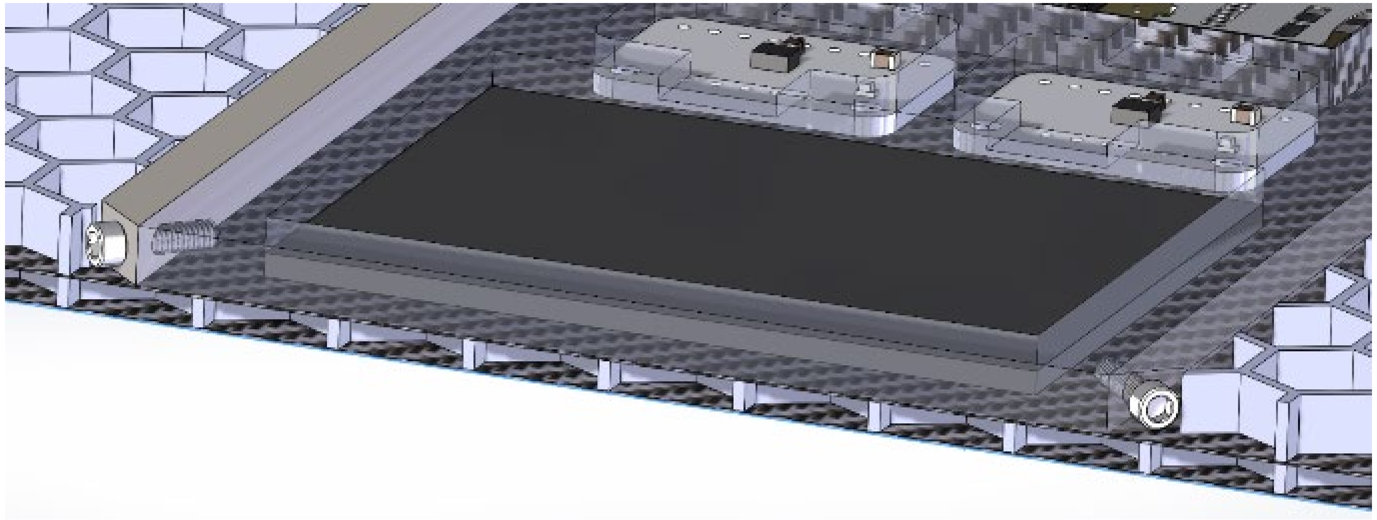
- Carbon Fiber sheets (0.2 mm)
  - Necessary for reinforcement of honevcomb structure
  - Epoxied with cyanoacrylate
- Guide rails
  - Aluminum 6061
    - Density: 2.7 g/cm³
    - Youngs Modulus: 69 GPa
    - Material Science and Engineering
  - High shear strength for preloading of fasteners

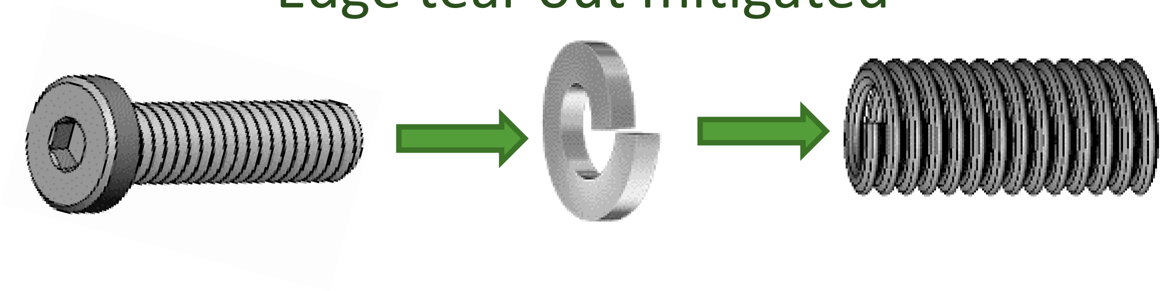


DR3.4- Unchanged C.O.G. ✓

Integration

- Slide fit
    - Tolerance of 0.005 in
- Fasteners
    - Loctite and lock washers
    - Helicoil
    - Preloading of 672 N
    - Edge tear out mitigated



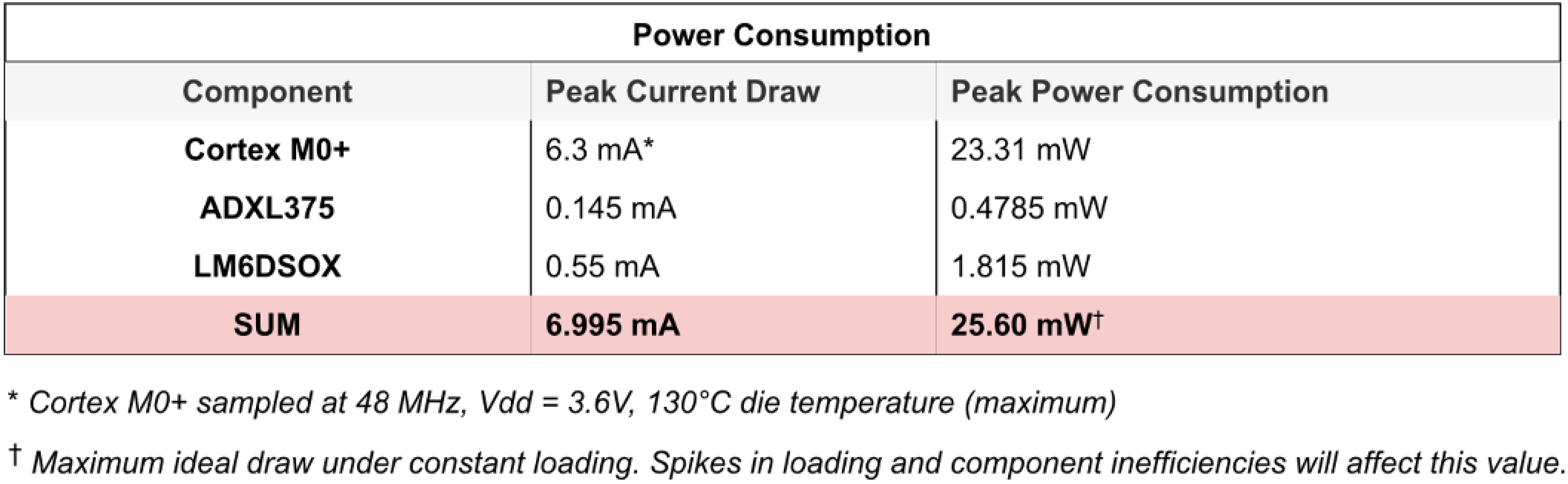


DR2.2 - No interference ✓

DR3.2 - Minimize sensor tray noise ✓

DR3.3 - Minimize mounting rail noise ✓

Power Budget



Power Consumption		
Component	**Peak Current Draw**	**Peak Power Consumption**
Cortex M0+	6.3 mA*	23.31 mW
ADXL375	0.145 mA	0.4785 mW
LM6DSOX	0.55 mA	1.815 mW
SUM	**6.995 mA**	**25.60 mW**[†]

** Cortex M0+ sampled at 48 MHz, Vdd = 3.6V, 130°C die temperature (maximum)*

[†] *Maximum ideal draw under constant loading. Spikes in loading and component inefficiencies will affect this value.*

85 hours Idealized Battery Life

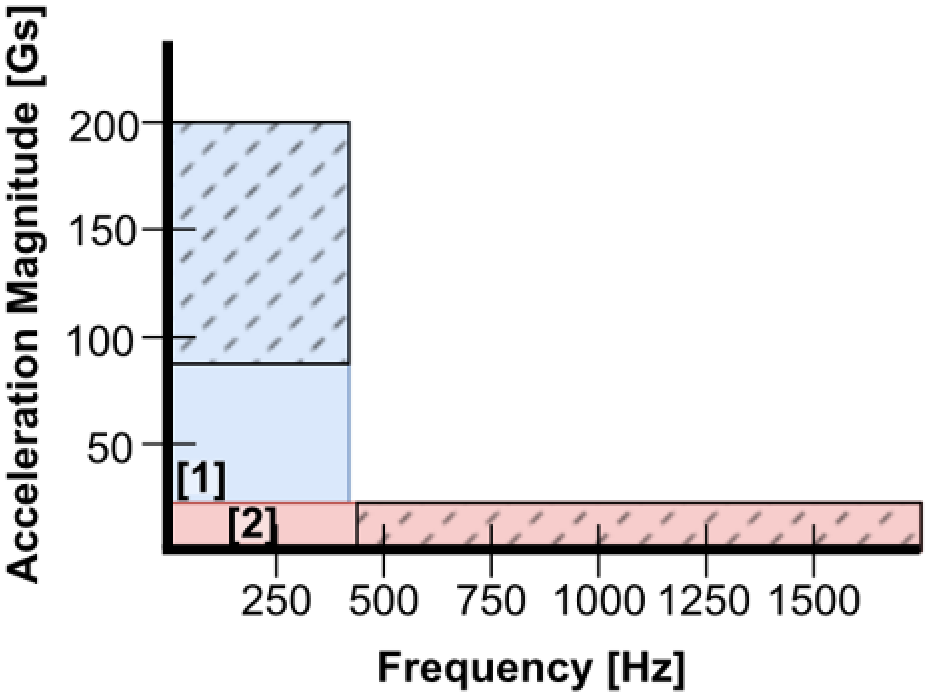
FR5 – Power & Thermal ✓

DR5.1 - 2 hours of power ✓

Sensing – Design Space

DR1.1 - 10% accuracy ✓

DR1.2 - 2x Nyquist Frequency ✓

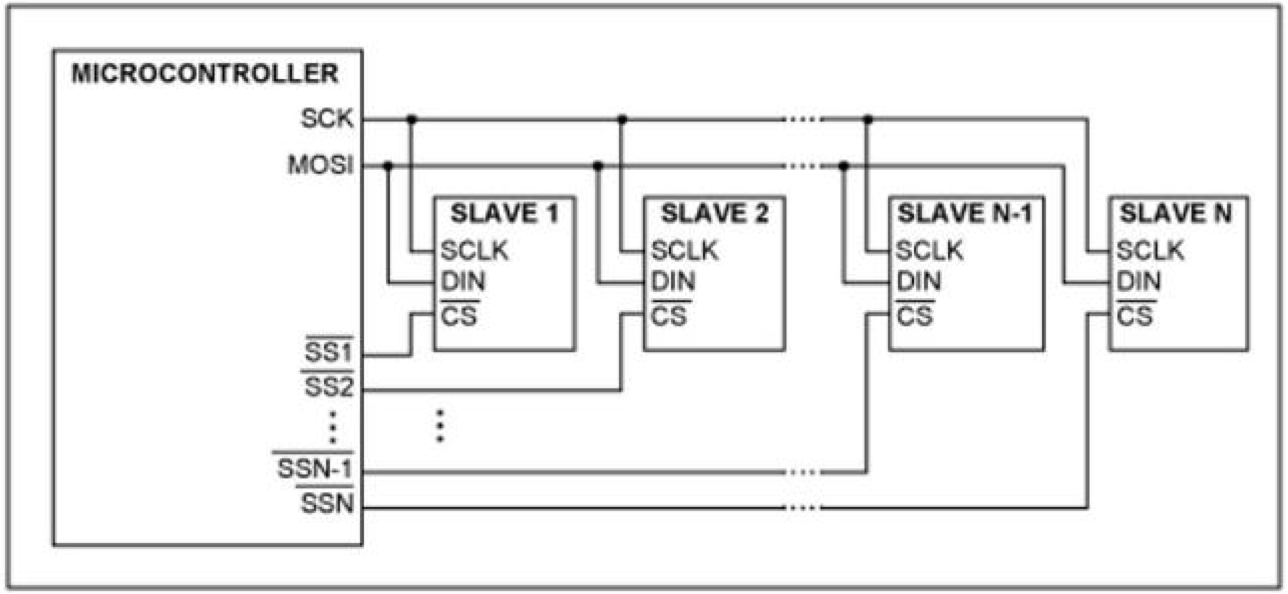


Region	Definition	Interest
[1]	Expected high-amplitude ROI	CPE 1
[2]	Expected high-frequency ROI	CPE 1
🟥	LM6DSOX sensing Capability	Sensing range of high-amplitude accelerometer
🟦	ADXL375 Sensing Capability	Sensing range of high-precision IMU
▨	Possible mission ROI	Additional sensing margin introduced to account for panel variability and multi-panel constructive resonance

Sensor Communication Interface

SPI Clock	2 MHz
SPI Mode	3 [Read Rising, Push Falling]

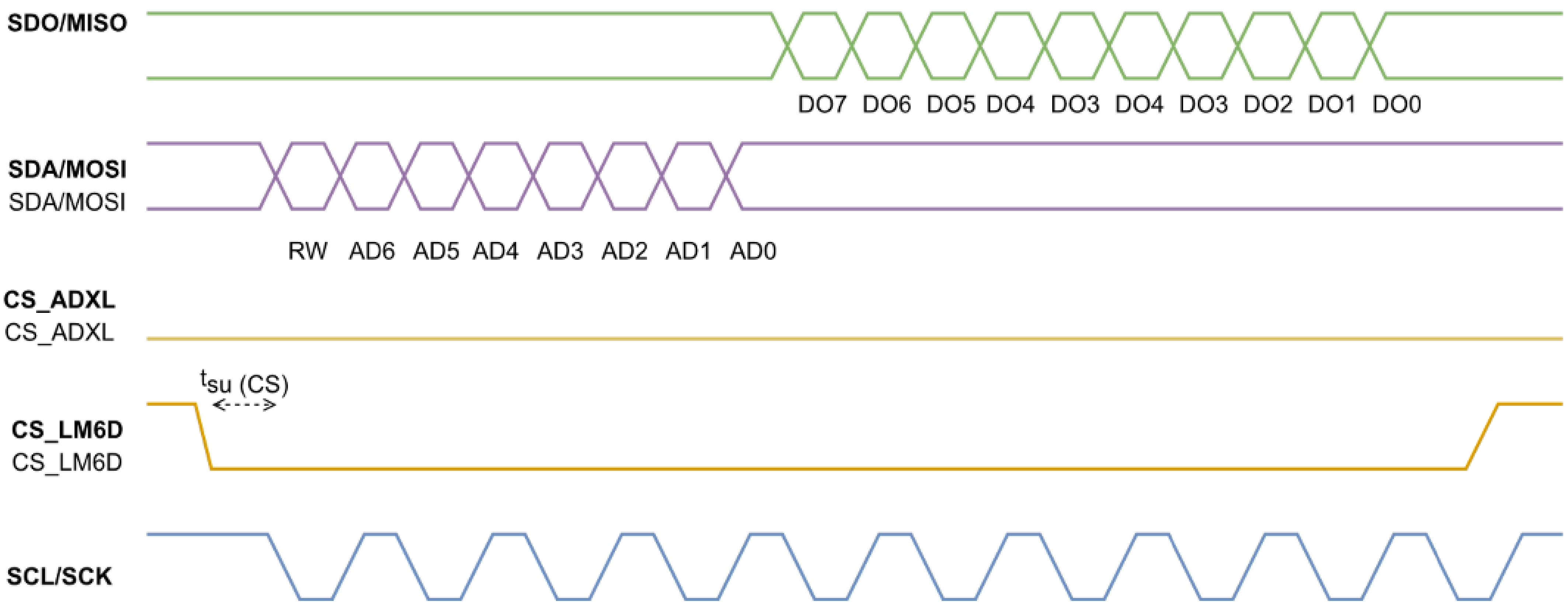
SPI Parallel Communications Layout



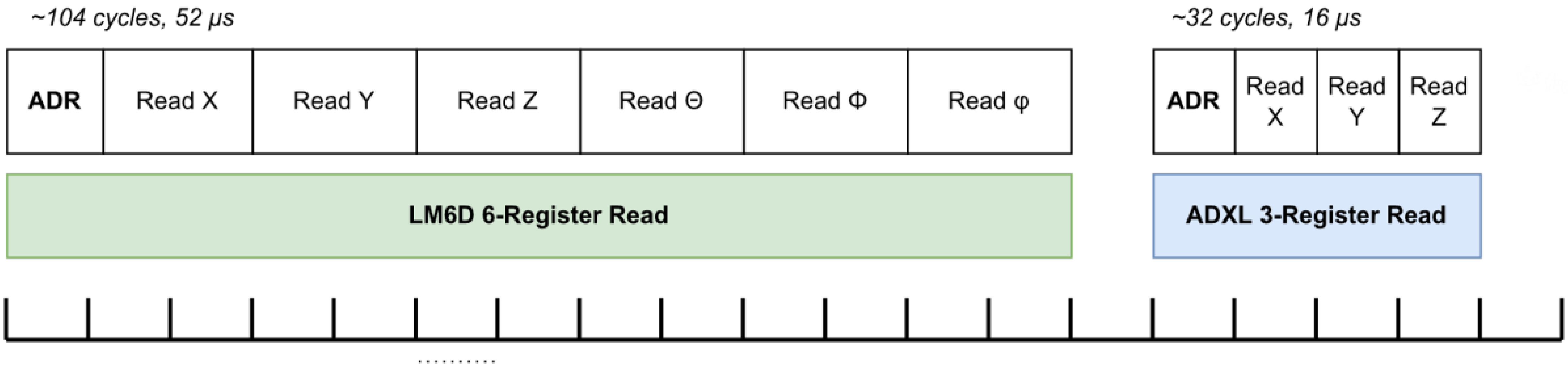
Link Budget & Communications

SPI MODE 3 - WIIGLS

SINGLE BYTE READ



Link Budget & Communications



~104 cycles, 52 μs

ADR
Read X
Read Y
Read Z
Read Θ
Read Φ
Read φ

LM6D 6-Register Read

~32 cycles, 16 μs

ADR
Read X
Read Y
Read Z

ADXL 3-Register Read

8-pulse interval

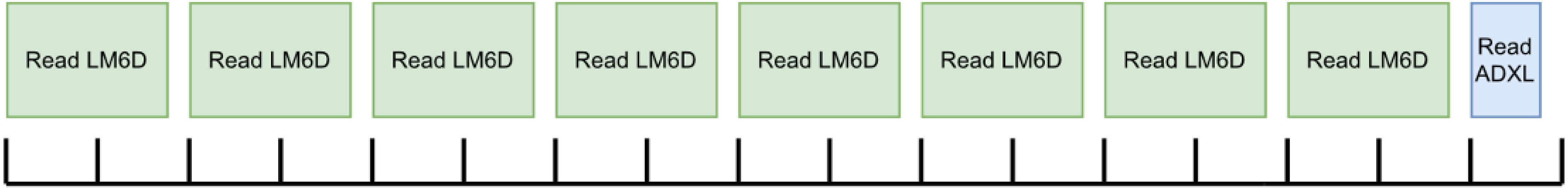
2 MHz clock timing

$t_{clk} = 500\ ns$

$t_{int} = 4\ \mu s$

Link Budget & Communications

8:1 register reads, LM6DSOX:ADXL375



Read LM6D

Read LM6D

Read LM6D

Read LM6D

Read LM6D

Read LM6D

Read LM6D

Read LM6D

Read ADXL

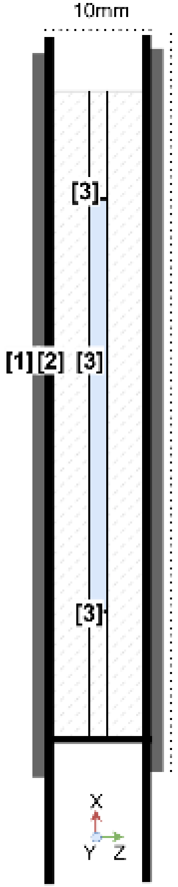
$t_{int} = 28\ \mu s$

$t_t = 476\ \mu s$

Effective Polling Rates, Maximum Bandwidth	
LM6DSOX	**16.8 KHz**
ADXL375	**2.1 KHz**

EMF Noise Mitigation

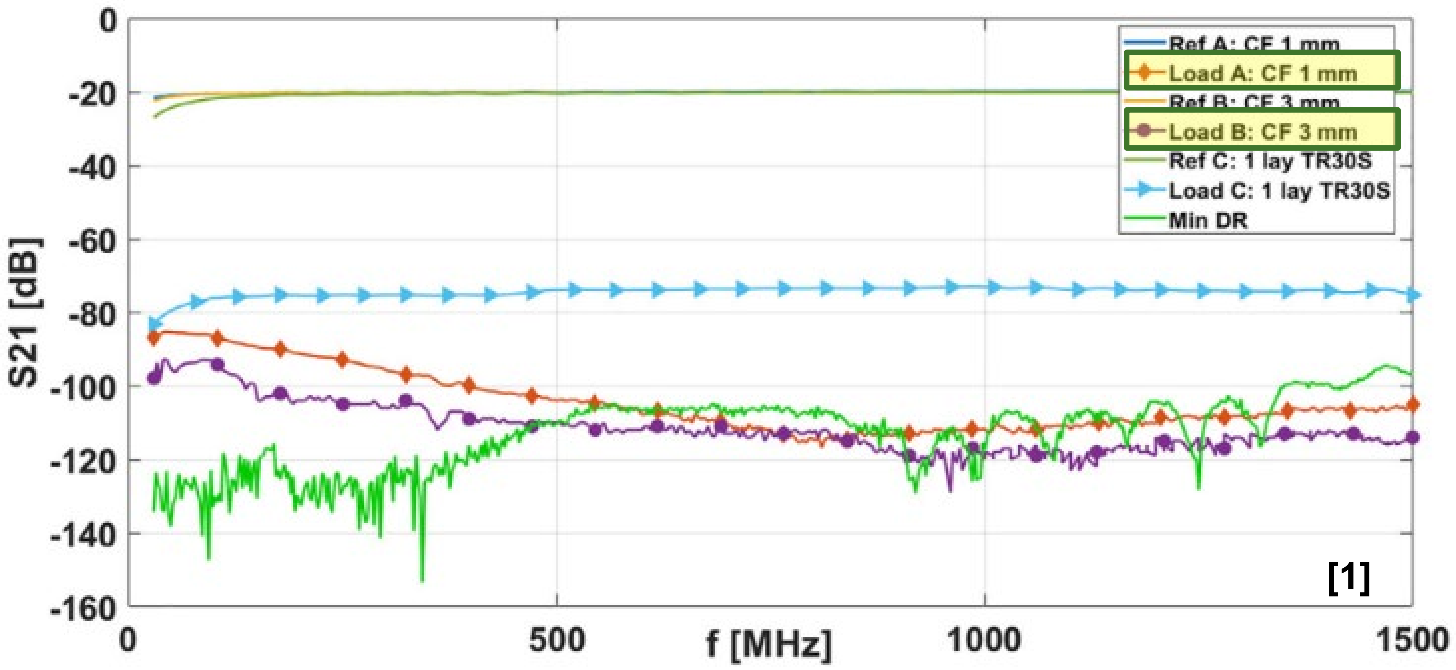
DR1.1 - 10% accuracy ✓



Legend	
[1]	2.5mm CF/Epoxy Laminate
[2]	0.2mm CF/Epoxy Laminate
[3]	0.2mm CF/Epoxy Laminate
🟦	Sensor Package

Expected EMF Attenuation

Axis	Attenuation
X	50 dB
Y	50 dB
Z	>80 dB



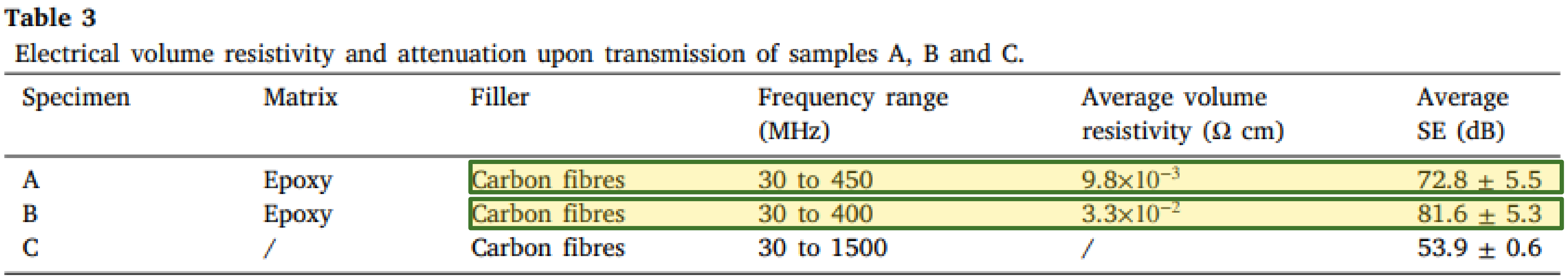


Table 3

Electrical volume resistivity and attenuation upon transmission of samples A, B and C.

Specimen	Matrix	Filler	Frequency range (MHz)	Average volume resistivity (Ω cm)	Average SE (dB)
A	Epoxy	Carbon fibres	30 to 450	9.8×10^{-3}	72.8 ± 5.5
B	Epoxy	Carbon fibres	30 to 400	3.3×10^{-2}	81.6 ± 5.3
C	/	Carbon fibres	30 to 1500	/	53.9 ± 0.6

[1]

[1] Munalli, D., Dimitrakis, G., Chronopoulos, D., Greedy, S., & Long, A. (2019). Electromagnetic shielding effectiveness of carbon fibre reinforced composites. *Composites Part B: Engineering*, *173*, 6–10. https://doi.org/10.1016/j.compositesb.2019.106906

Verification & Validation

Madison Ritsch

V&V: Overall Objectives

3 Types of Verification:

1. Static Sensor Noise Verification
2. Frequency Response Verification
3. Fully Integrated Prototype Verification

2 Types of Validation:

1. Suite Insertion and Removal Process Validation
2. Power & Thermal Validation

Static Sensor Noise Verification

Objective:

- Quantify internal and external noise
- Verifying it will not interfere with accurate data collection

Plan:

1. Place entire system flat on a table
2. Record data for 2 minutes
3. Analyze data to determine static noise for each sensor

FR1 – Data Collection ☑

DR1.1.1 – SNR < 20 dB ☑

Pass Criteria:

- Signal-to-noise ratio > 20 dB for all expected motion & vibrations

Testing Facility & Equipment:

- AERO 309A
- Fully integrated panel
  - Machined by Nate and Team

Frequency Response Verification

Objective:

- Verify fully integrated panel measured frequencies match vibe table input frequencies
  - No induced structural resonance
- Ensure suite can undergo expected frequencies without failure

Plan:

1. Shake both fully integrated panel and unmodified panel on vibe table
   - Frequency sweep from 0 to 500 Hz at a fixed amplitude
2. Record data throughout tests
3. Visually inspect panel sensor suite after test

Pass Criteria:

- Response frequencies within 10% of vibe table input frequency in frequency region of interest
- Fasteners still fixed - marks on nuts and bolts
- Electrical connections still functional – multimeter test

Testing Facility & Equipment:

- PILOT Lab Vibe Table
- Fully Integrated Panel
  - Machined by Nate and Team

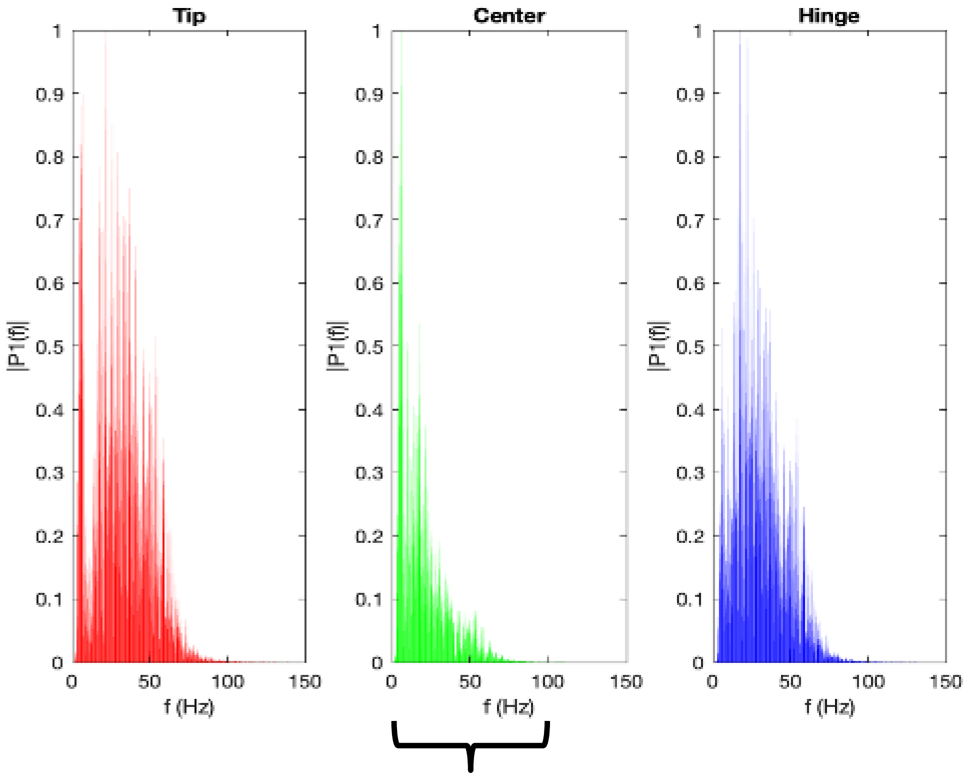
FR3 – Integration ☑

DR3.1.1 – Sensors within 10% ☑

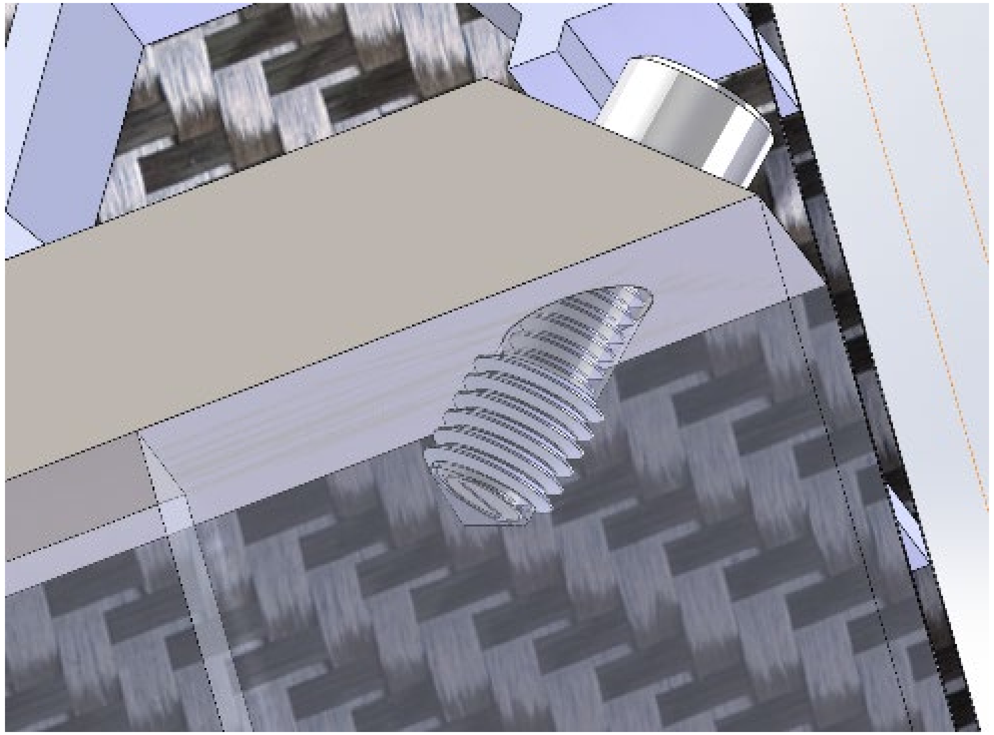
DR3.2.1 – Tray resonance within 10% ☑

DR3.3.1 – System within 10% of input frequencies ☑

Frequency Response Verification



Expected Frequency ROI : 0-100Hz



Suite Design Goal:

- Minimize structural resonance within panel & attachment points
- Transmit all panel vibrations to sensor suite

Fully Integrated Prototype Verification

- Objective:
  - Verify data is collected and stored throughout entire test
  - Ensure all exhibited behavior is captured
  - Ensure suite remains functional enough for repetition
  - Verify recorded data between panels is within 10% of each other
- Plan:
  1. Execute 5 full deployments with unmodified panel using teardrop accelerometers
  2. Execute 5 full deployments with fully integrated prototype
- Pass Criteria:
  - Data is recorded and stored onboard throughout entire deployment
  - Suite remains in working condition after deployment
- Testing Facility & Equipment:
  - AERO 309A Deployment Setup
  - Fully Integrated Panel
    - Machined by Nate and Team

FR1 – Data Collection ✓

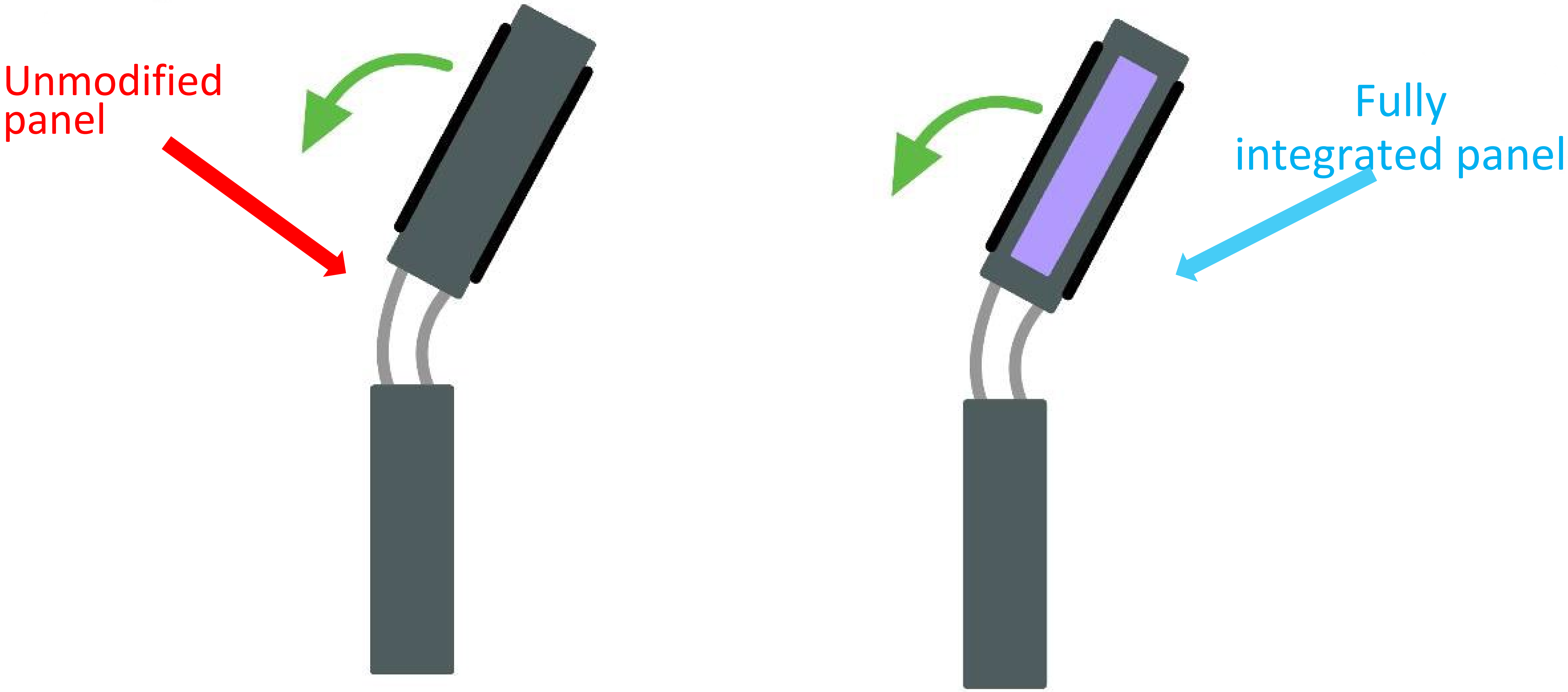
DR1.1 - Deployment dynamics within 10% ✓

DR1.2 – 2x Nyquist frequency ✓

DR1.3.1 – Shock up to 200 Gs ✓

DR1.3.2 – Sensors remain secure ✓

V&V: Fully Integrated Prototype Test



Suite Insertion & Removal Validation

- Objective:
  - Establish that suite can be inserted and removed in 5 minutes
- Plan:
  1. Time 5 insertion and removal attempts
  2. Deploy suite immediately after insertion and removal cycles to ensure no functional damage
- Pass Criteria:
  - Suite can be inserted and removed in 5 minutes without damage
  - Panel deployment dynamics remain unchanged after insertion and removal
- Testing Facility & Equipment:
  - AERO 309A Deployment Setup
    - Fully Integrated Panel
      - Machined by Nate and Team

FR4 – Ease of Use ✓

DR4.1 - Installation Time ✓

DR4.1.1 – Safely Accessed ✓

Power & Thermal Validation

- Objective:
  - Ensure battery can survive 1 hour active testing & 1 hour passive standby
  - Ensure electronics have enough ventilation to maintain usable operating temperature
- Plan:
  1. Start 2 hour timer
  2. Deploy powered panel one time
  3. Let panel rest for remaining time while recording data & processor temperature
- Pass Criteria:
  - Battery voltage above 3.4V after complete 2 hour test
    - 2 hours of active testing and data recording = increased FS on 1 hour active testing & 1 hour passive standby
- Testing Facility:
  - AERO 309A Deployment Setup
  - Fully Integrated Panel
    - Machined by Nate and Team

ΔT = 0.002°C

FR5 – Power ✓

DR5.1 - Operating Temp. ✓

DR5.2 - Battery Voltage ✓

Project Planning

Olivia Epstein

WIIGLS

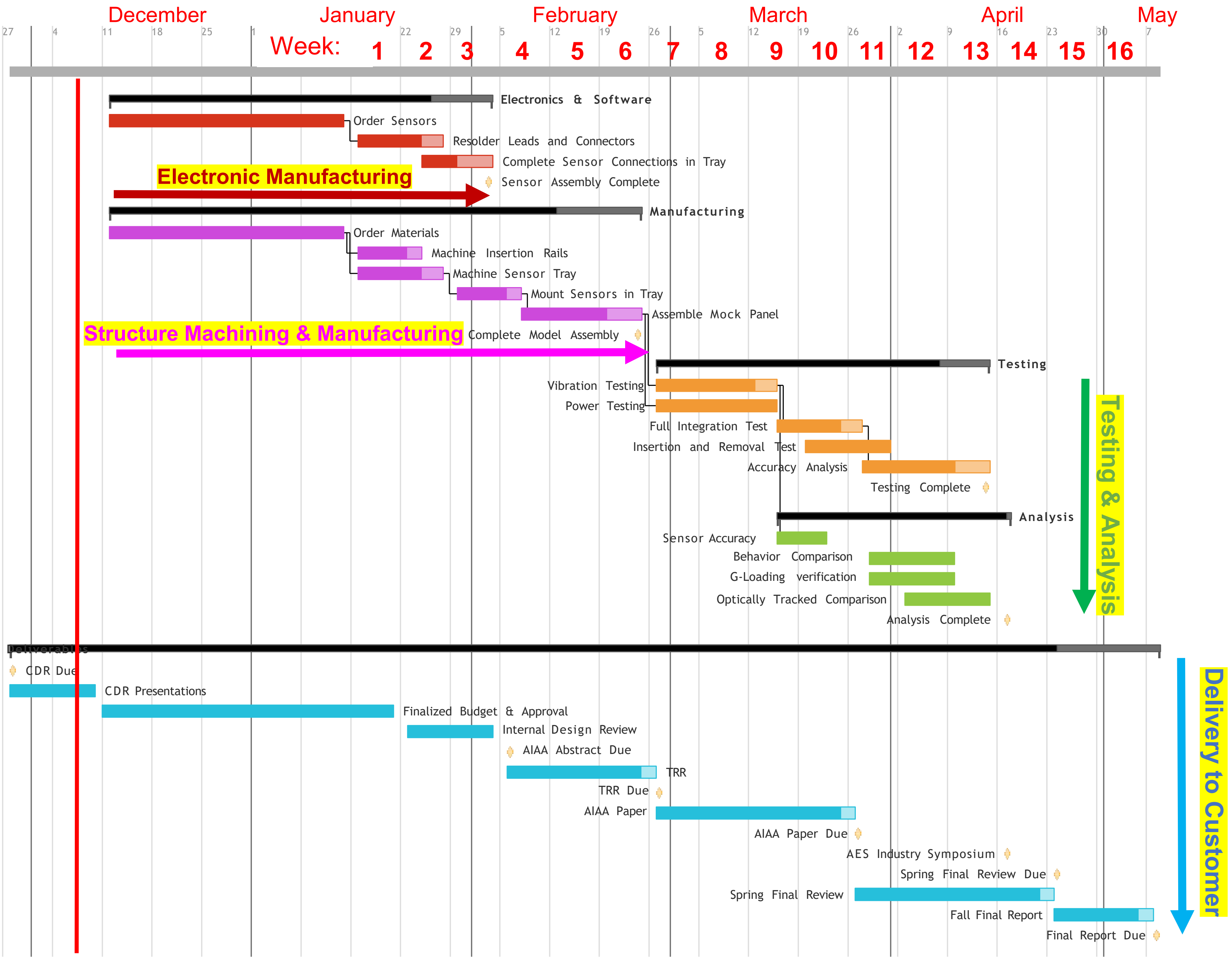
Electronics & Software
- Order Sensors
- Resolder Leads and Connectors
- Complete Sensor Connections in Tray
- Sensor Assembly Complete

Manufacturing
- Order Materials
- Machine Insertion Rails
- Machine Sensor Tray
- Mount Sensors in Tray
- Assemble Mock Panel
- Complete Model Assembly

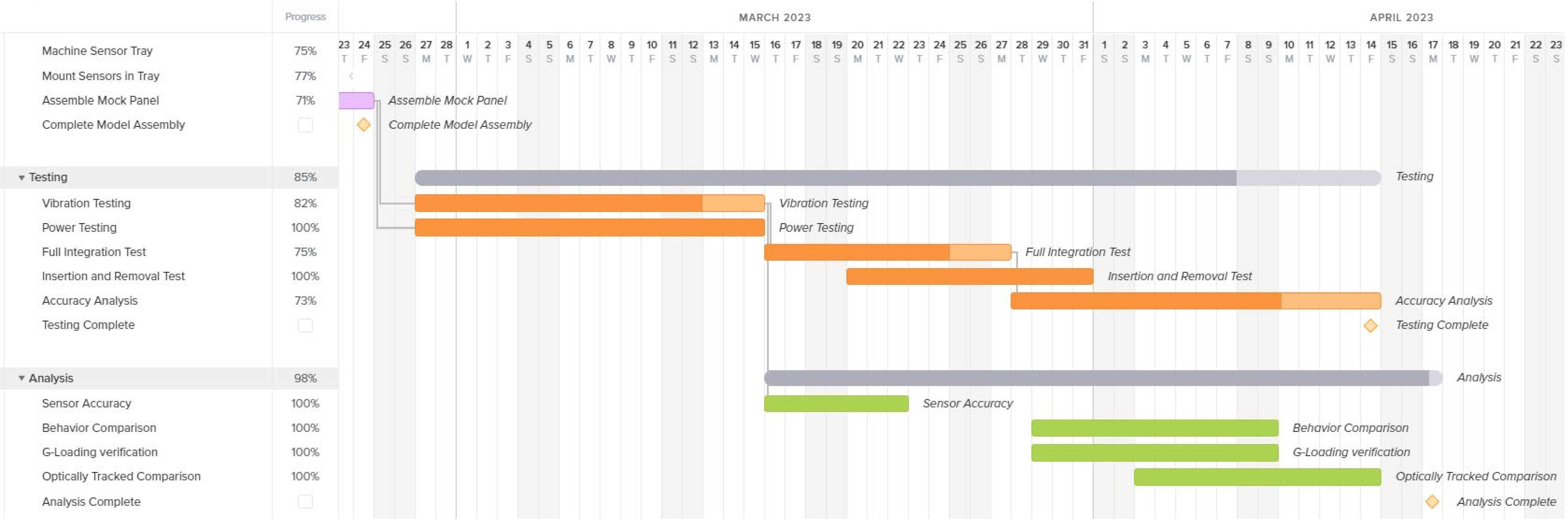
Testing
- Vibration Testing
- Power Testing
- Full Integration Test
- Insertion and Removal Test
- Accuracy Analysis
- Testing Complete

Analysis
- Sensor Accuracy
- Behavior Comparison
- G-Loading verification
- Optically Tracked Comparison
- Analysis Complete

Deliverables
- CDR Due
- CDR Presentations
- Finalized Budget & Approval
- Internal Design Review AIAA
- Abstract Due
- TRR
- TRR Due
- AIAA Paper
- AIAA Paper Due
- AES Industry Symposium
- Spring Final Review Due
- Spring Final Review
- Fall Final Report
- Final Report Due



Testing Timeline

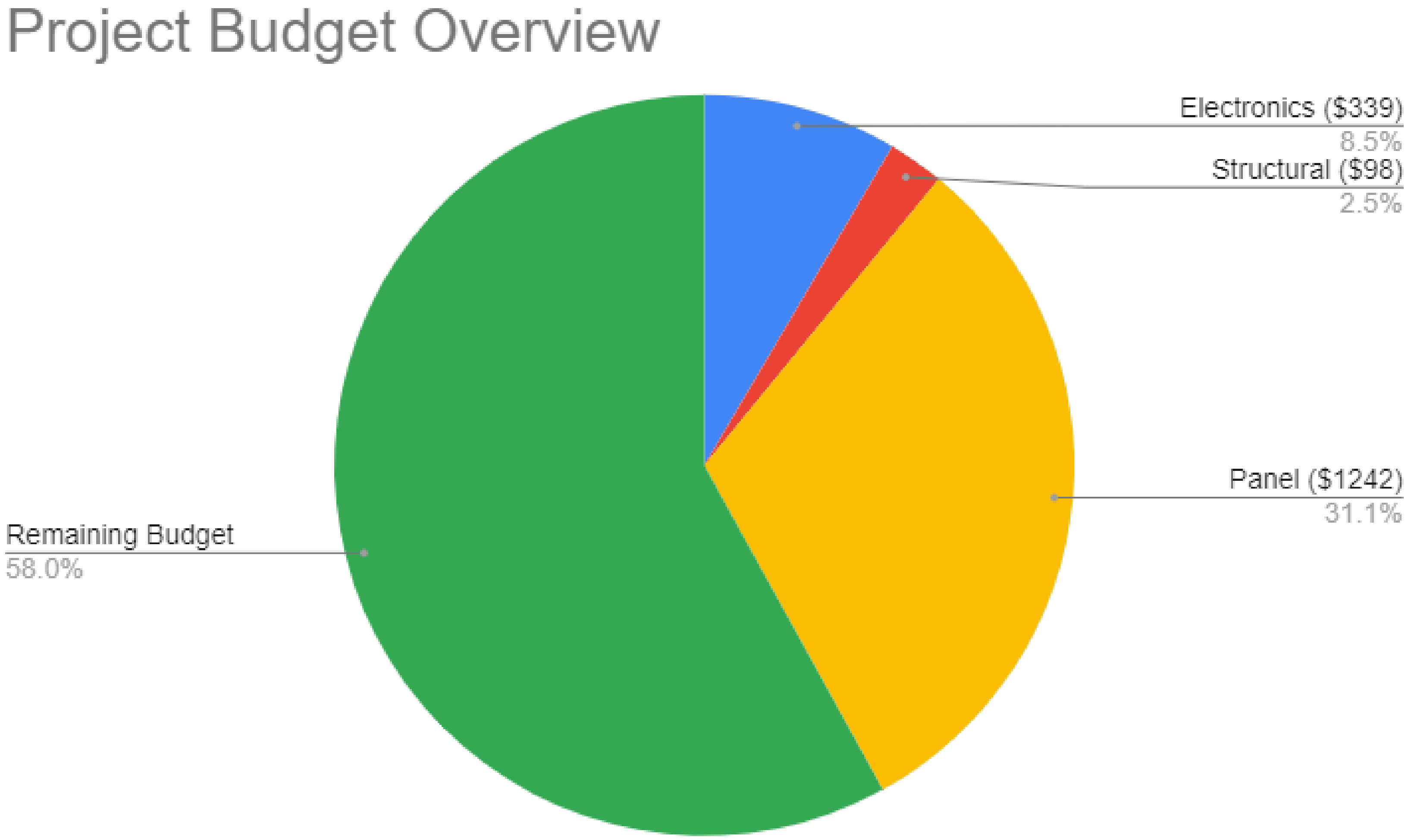


	Progress
Machine Sensor Tray	75%
Mount Sensors in Tray	77%
Assemble Mock Panel	71%
Complete Model Assembly	☐
▾ Testing	85%
Vibration Testing	82%
Power Testing	100%
Full Integration Test	75%
Insertion and Removal Test	100%
Accuracy Analysis	73%
Testing Complete	☐
▾ Analysis	98%
Sensor Accuracy	100%
Behavior Comparison	100%
G-Loading verification	100%
Optically Tracked Comparison	100%
Analysis Complete	☐

Test Plan

Test	CPE Addressed	Output(s)	Scheduling	
			Location	Estimated Date
Sensor Noise	CPE1: Sensor Capabilities CPE4: Accuracy	Data noise, data accuracy	AERO 309A	February 2023
Frequency Response	CPE1: Sensor Capabilities CPE4: Accuracy	Accurate frequency measurements, fastener security, electrical connections	PILOT Lab Vibe Table	March 2023
Deployment	CPE1: Sensor capabilities CPE3: Integration CPE4: Accuracy	Motion accuracy, sensing capabilities in range, data capture	AERO 309A	March 2023
Insertion/Removal	CPE3: Integration	Within allocated time, hardware is not damaged, data extraction	AERO 309A	March 2023
Power/Thermal	CPE2: Power Source	Voltage remains nominal, temperatures so not effect system	AERO 309A	March 2023

Cost Plan



Budget Breakdown:

Structural: (M = $50)

- Raw Materials
- Hardware

Electronics: (M = $50)

- Sensors/Battery
- Microprocessor

Panel: (M = $400)

- Carbon Fiber Sheets
- Honeycomb

Remaining: $2320

Acknowledgements

Team WIIGLS would like to thank Dr. Erik Knudsen, Dr. Francisco López Jiménez, Yasara Dharmadasa, Professor Trudy Schwartz, Professor Wingate, Nate Coyle, and the TFs for their guidance, mentoring, and contributions to this presentation.

THANK YOU!

Thank you

Any Questions?

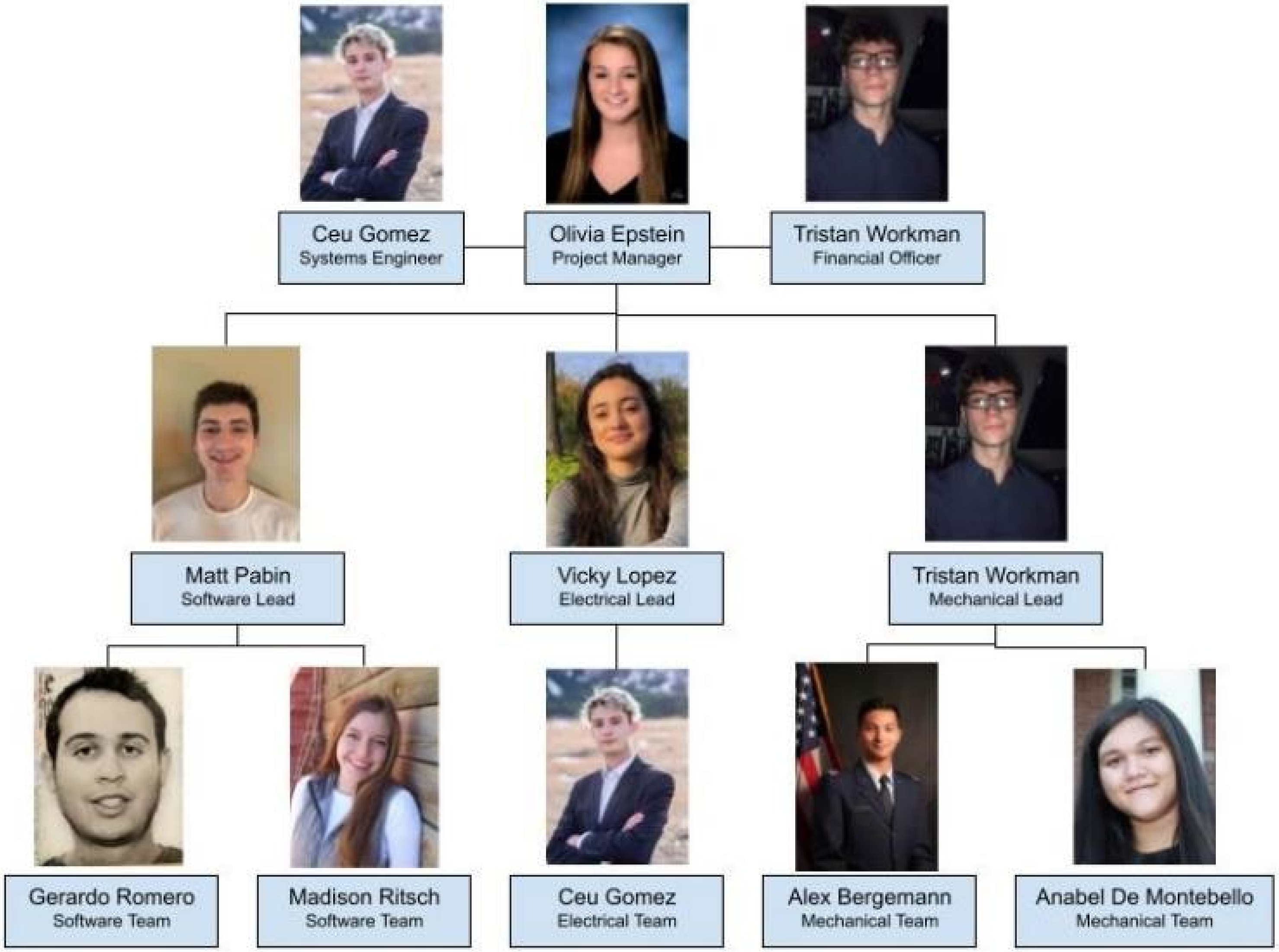
Appendix & Supporting Materials

Appendix Contents

- Administrative
- Detailed FR's and DR's
- Additional Analysis
  - Mechanical
  - Electrical
  - G-Loading
  - Frequencies
- Trade Studies
- Linked Works Cited

Administrative

Team Organization



Ceu Gomez
Systems Engineer

Olivia Epstein
Project Manager

Tristan Workman
Financial Officer

Matt Pabin
Software Lead

Vicky Lopez
Electrical Lead

Tristan Workman
Mechanical Lead

Gerardo Romero
Software Team

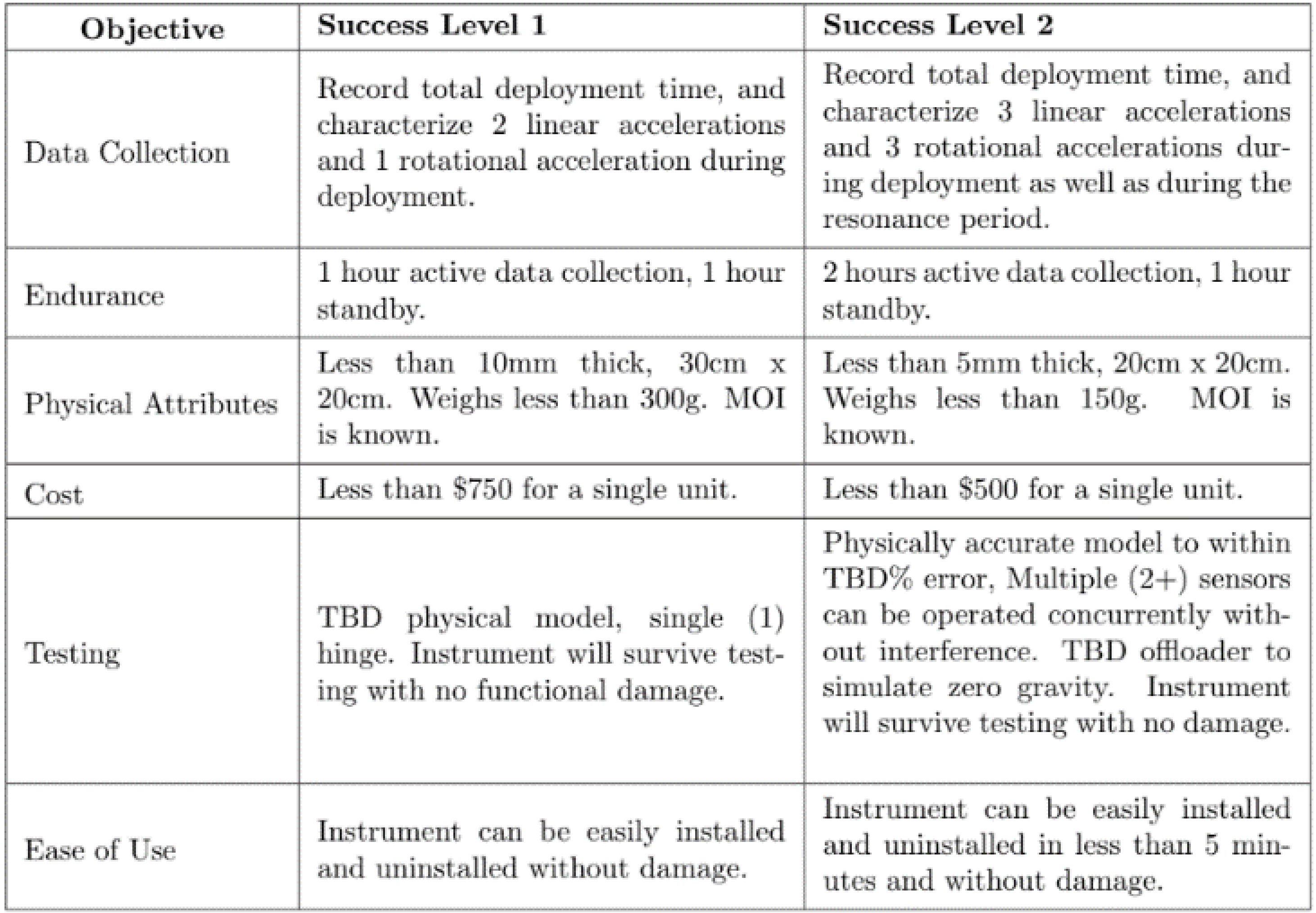
Madison Ritsch
Software Team

Ceu Gomez
Electrical Team

Alex Bergemann
Mechanical Team

Anabel De Montebello
Mechanical Team

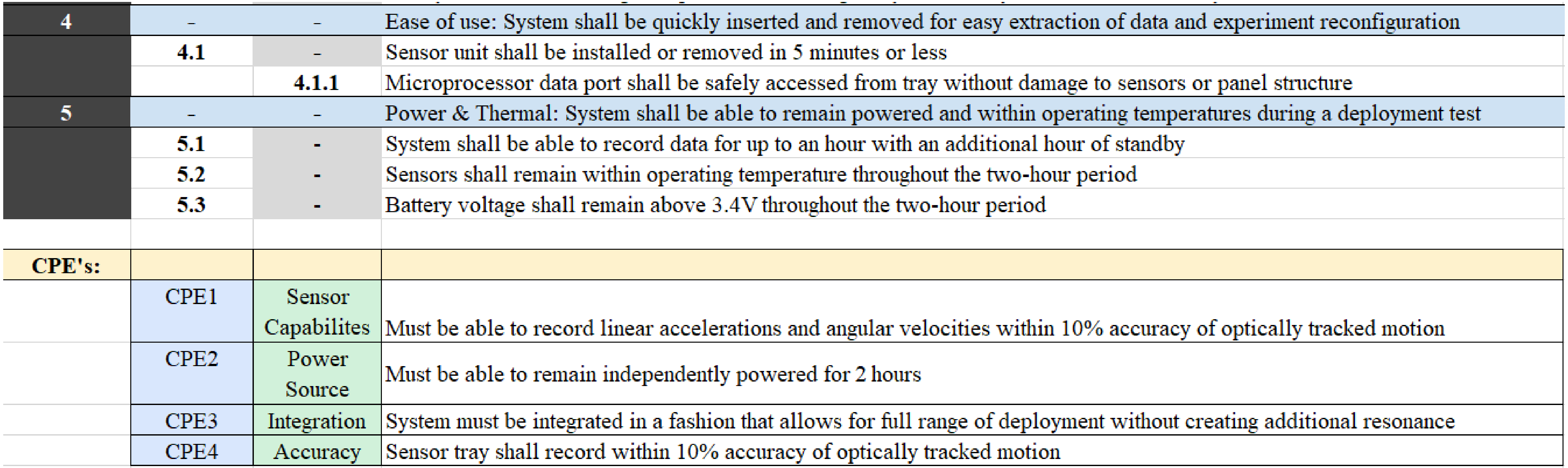
Levels of Success



Objective	Success Level 1	Success Level 2
Data Collection	Record total deployment time, and characterize 2 linear accelerations and 1 rotational acceleration during deployment.	Record total deployment time, and characterize 3 linear accelerations and 3 rotational accelerations during deployment as well as during the resonance period.
Endurance	1 hour active data collection, 1 hour standby.	2 hours active data collection, 1 hour standby.
Physical Attributes	Less than 10mm thick, 30cm x 20cm. Weighs less than 300g. MOI is known.	Less than 5mm thick, 20cm x 20cm. Weighs less than 150g. MOI is known.
Cost	Less than $750 for a single unit.	Less than $500 for a single unit.
Testing	TBD physical model, single (1) hinge. Instrument will survive testing with no functional damage.	Physically accurate model to within TBD% error, Multiple (2+) sensors can be operated concurrently without interference. TBD offloader to simulate zero gravity. Instrument will survive testing with no damage.
Ease of Use	Instrument can be easily installed and uninstalled without damage.	Instrument can be easily installed and uninstalled in less than 5 minutes and without damage.

Detailed Requirements

FR	DR1	DR2	Requirement
1	-	-	Data Collection: System shall accurately measure and store motion and natural frequencies of ground-based panel deployment
	1.1	-	System shall record deployment dynamics to within 10% of optically tracked motion
	-	**1.1.1**	System shall maintain a signal-to-noise ratio of less than 20 dB
	1.2	-	Sensors shall be capable of recording accelerations at minimum 2x the Nyquist frequency of panel deployment
	1.3	-	System shall survive deployment forces
	-	**1.3.1**	System shall endure a shock of up to 200 Gs without structural damage
	-	**1.3.2**	Sensors shall remain secure when exposed to deployment forces
	-	**1.3.3**	Mounting fasteners shall survive forces and shocks up to 200 N and 200 Gs respectively
2	-	-	Size & Mass: Sensor tray shall fit within the allocated panel space and weigh less than150g without obstructing deployment
	2.1	-	Sensor unit shall not exceed a volume of 200 x 150 x 5 mm
	2.2	-	Sensor unit installation method shall not interfere with deployment
	2.3	-	System shall have a known moment of inertia
3	-	-	Integration: System shall be integrated into structure to be tested such that the underlying kinematics of the structure remain
	3.1	-	Sensors shall be mounted to sensor tray securely to minimize data noise and prevent resonance induced inaccuracies
	-	**3.1.1**	Sensors shall record vibrations accurately within 10% of optically tracked motion
	3.2	-	Sensor tray shall be fastened securely to mounting rails to minimize data noise and prevent resonance induced inaccuracies
	3.3	-	Mounting rails shall be securely adhered to panel interior to minimize data noise and prevent resonance induced inaccuracies
	-	**3.3.1**	The system shall experience vibrations within 10% of input vibrations
	3.4	-	The system shall not change the panel's center of gravity location by more than 5 mm in any direction

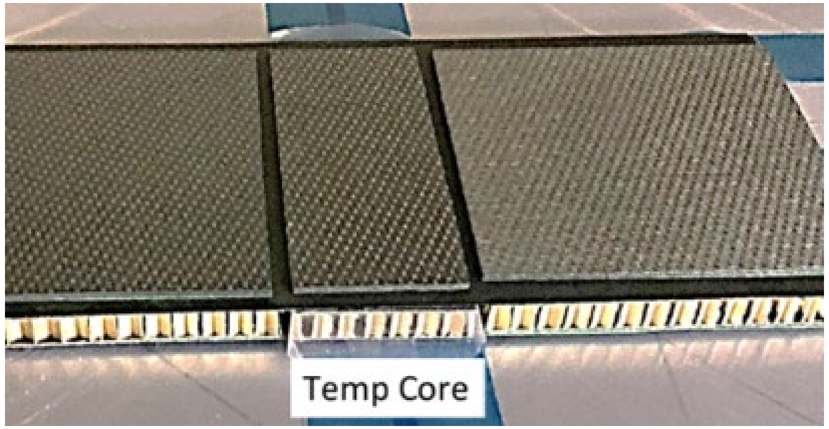


4	-	-	Ease of use: System shall be quickly inserted and removed for easy extraction of data and experiment reconfiguration
	4.1	-	Sensor unit shall be installed or removed in 5 minutes or less
		4.1.1	Microprocessor data port shall be safely accessed from tray without damage to sensors or panel structure
5	-	-	Power & Thermal: System shall be able to remain powered and within operating temperatures during a deployment test
	5.1	**-**	System shall be able to record data for up to an hour with an additional hour of standby
	5.2	**-**	Sensors shall remain within operating temperature throughout the two-hour period
	5.3	**-**	Battery voltage shall remain above 3.4V throughout the two-hour period
CPE's:			
	CPE1	Sensor Capabilites	Must be able to record linear accelerations and angular velocities within 10% accuracy of optically tracked motion
	CPE2	Power Source	Must be able to remain independently powered for 2 hours
	CPE3	Integration	System must be integrated in a fashion that allows for full range of deployment without creating additional resonance
	CPE4	Accuracy	Sensor tray shall record within 10% accuracy of optically tracked motion

Additional Analysis: Structures

Manufacturing Feasibility & Process

1. Epoxy top sheet carbon fiber to hinge coupon
2. Epoxy honeycomb layers to hinge coupon
3. Epoxy rails to honeycomb around temporary core
4. Sandwich honeycomb by epoxying additional carbon fiber sheet to honeycomb
5. Epoxy honeycomb to top and bottom of step 1 & step 3 carbon fiber sheets
6. Epoxy carbon fiber hinge panel to step 4 honeycomb using temp core to fix dimensions
7. Epoxy reinforcement carbon fiber to step 5 carbon fiber hinge panel above each side of honeycomb



Size & Mass

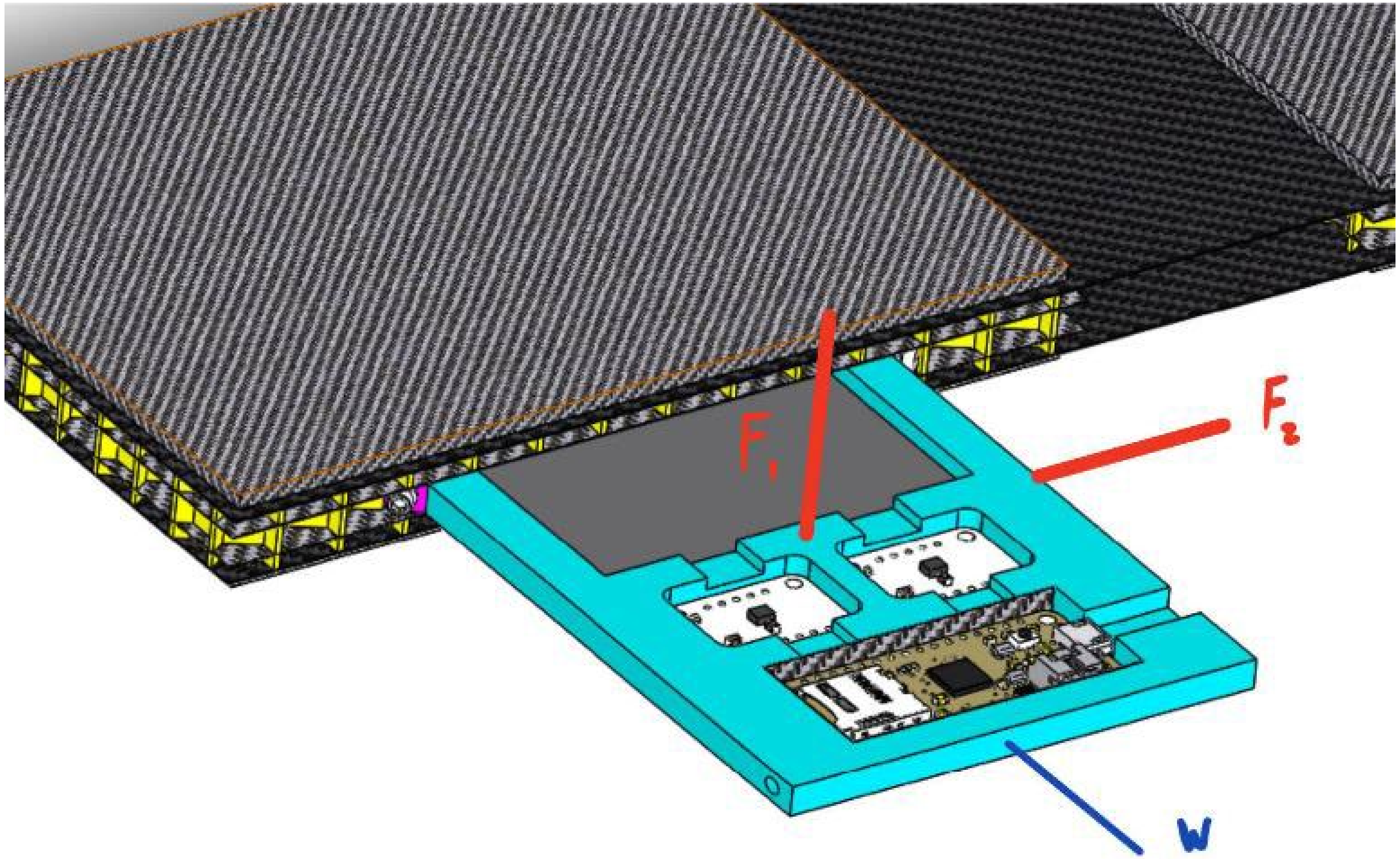
Electronics

	LSM6DSOX (IMU)	**ADXL375 (Accelerometer)**	**Microprocessor (Adafruit Featherlogger M0)**	**Battery**
Dimensions [mm]	25.6x17.8x2	25.6x17.8x2	51x23x3	69x45x2
Mass [g]	1.7	1.7	4.7	9

Structure

	Sensor Suite Tray	**Guide Rails**	**Hardware (HeliCoils + Fasteners)**
Dimensions [mm]	117.8 x 81.8 x 5	117.8 x 5 x 5	n/a
Mass [g]	31.86	15.04	2.6

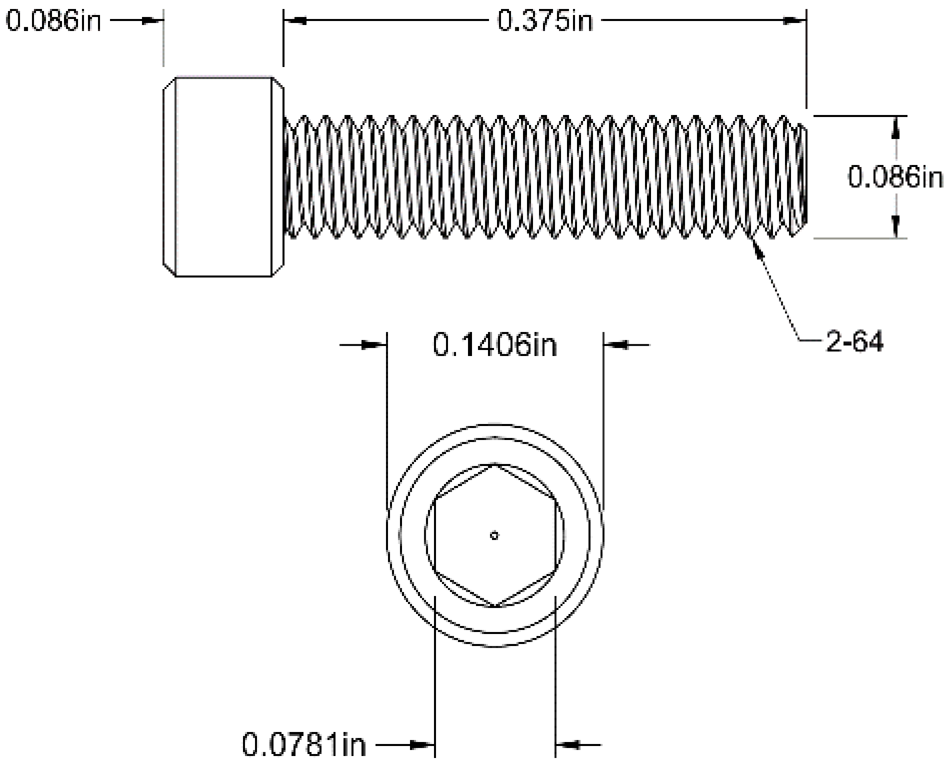
Suite Free Body Diagram



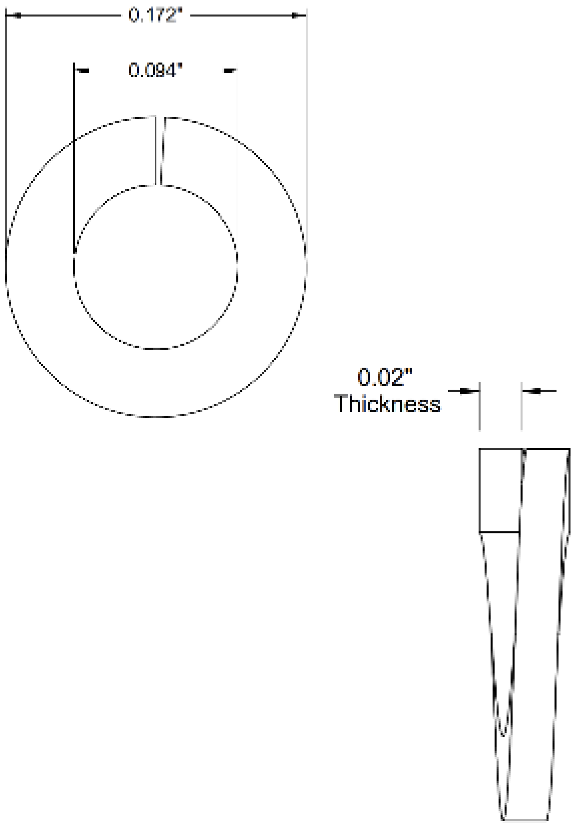
$F_1 = F_2 = 441$ N
$W < 1$ N

Fastener Parts

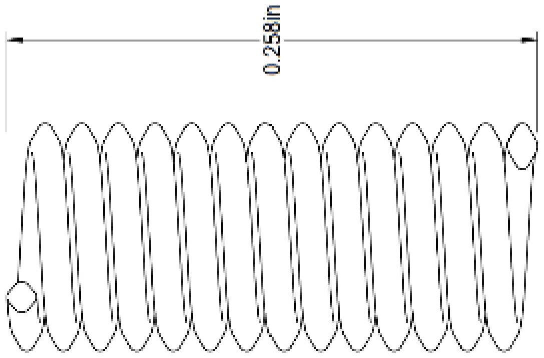
Screw



Lock Washer



Helicoil



Fastener Failures

Safety factors of 67 – 640

- Axial tear out

$$F = A_t\,\sigma = 0.00394 * 170,000 = 670\;lbs = 2980\;N$$

- Shear on head

$$F = A_h\tau = \pi r_h^2\tau = \pi 0.1406^2 * 0.6 * 170,000 = 6335\;lbs = 28,180\;N$$

- Shear on body

$$A_s = 0.5\pi d_r n_t\,p = 0.5\pi * 0.0657 * 17 * (1/64) = 0.0274\;in = 0.7000\;mm$$

$$F = A_s\tau = 0.0274 * 0.6 * 170,000 = 2796\;lbs = 12,437\;N$$

Fastener Preload and Torque

- Preload

$$F_i = 0.75F_p = (0.75A_t)(0.85S_y) = (0.75 * 0.00394)(0.85 * 60,000) = 151\ lbs = 672\ N$$

- Required Torque

$$T = KF_id = 0.3 * 151 * 0.086 = 3.89\ lb \cdot in = 0.44\ Nm$$

Edge Tear out

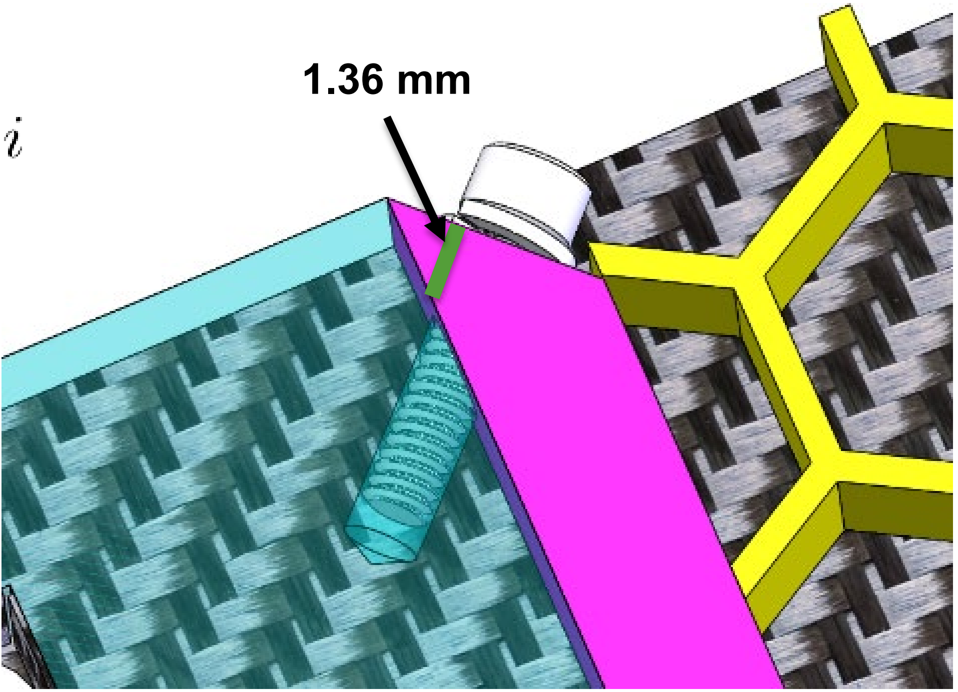
- Fastener Hole in Aluminum 6061

$$\tau = \frac{F_i}{A_s} = \frac{672}{1.5(2*\pi*0.0021844*0.001363)} = 24\ MPa = 3.47E9\ psi$$

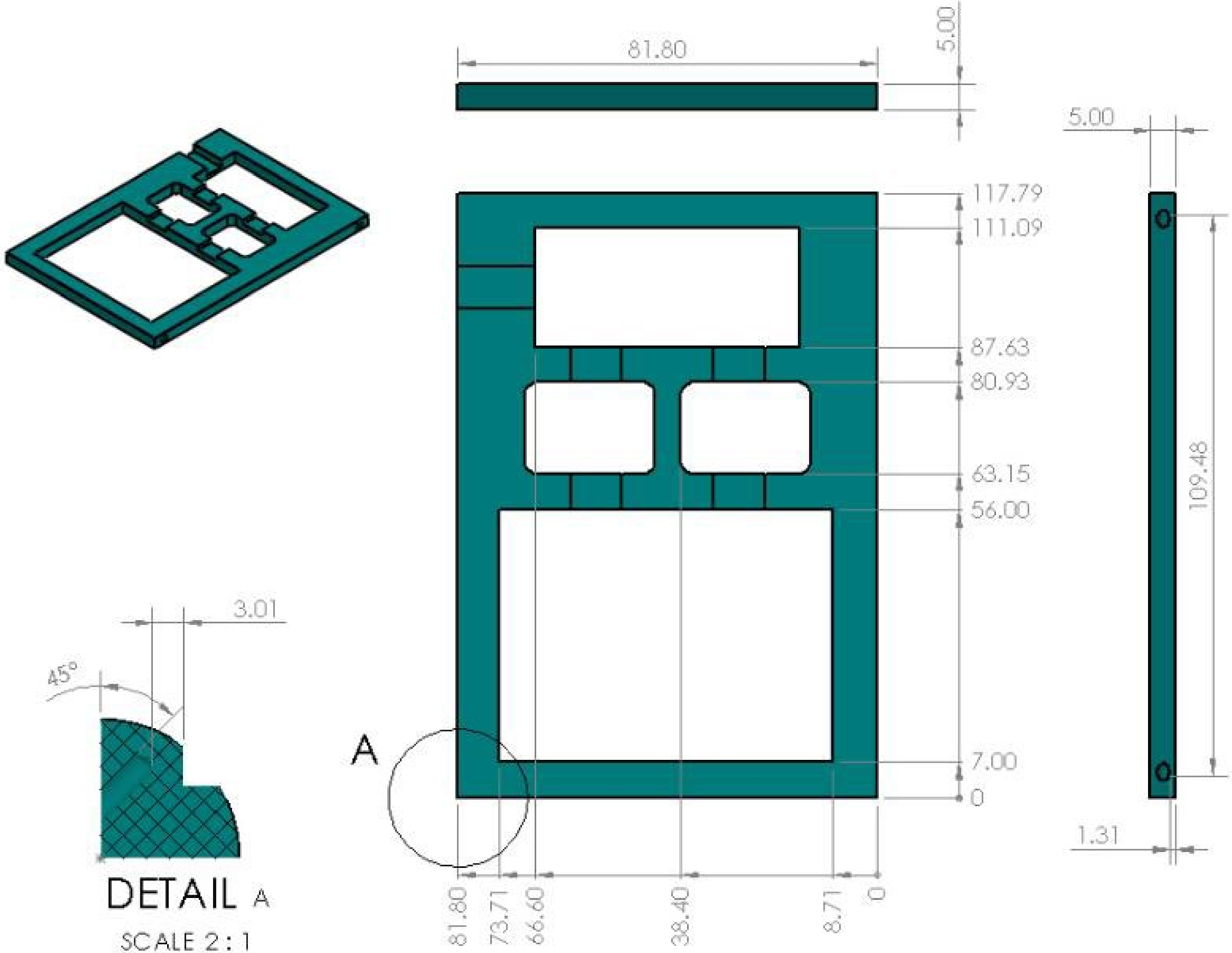
- Worst Case Scenario

$$\tau = \frac{F_i}{A_s} = \frac{672}{(0.005*0.001363)} = 98.6\ MPa = 14.3E9\ psi$$

  - 206 MPa 6061 Shear Strength (Mechanics of Materials)
  - 276 MPa 6061 Yield Strength (Materials Science and Engineering)
  - 2.08 Factor of Safety for worst case



Edge Tear out



Thermal Expansion

- Parallel

$$\Delta L = \alpha L_0 \Delta T = 110E - 6 * 118 * 0.002 = 2.60E - 5\,mm$$

$$\Delta L = \alpha L_0 \Delta T = 110E - 6 * 82 * 0.002 = 1.80E - 5\,mm$$

- Normal

$$\Delta L = \alpha L_0 \Delta T = 110E - 6 * 5 * 0.002 = 1.10E - 6\,mm$$

Epoxy Analysis

- 30 G's peak acceleration
  - SF = 10, 300 G's peak acceleration
- Cured epoxy shear strength greater than 5 N/mm²
- Electronics FS range = 64 to 492
- Aluminum rails to carbon fiber
  - FS = 32
- Plenty of room for real world manufacturing errors

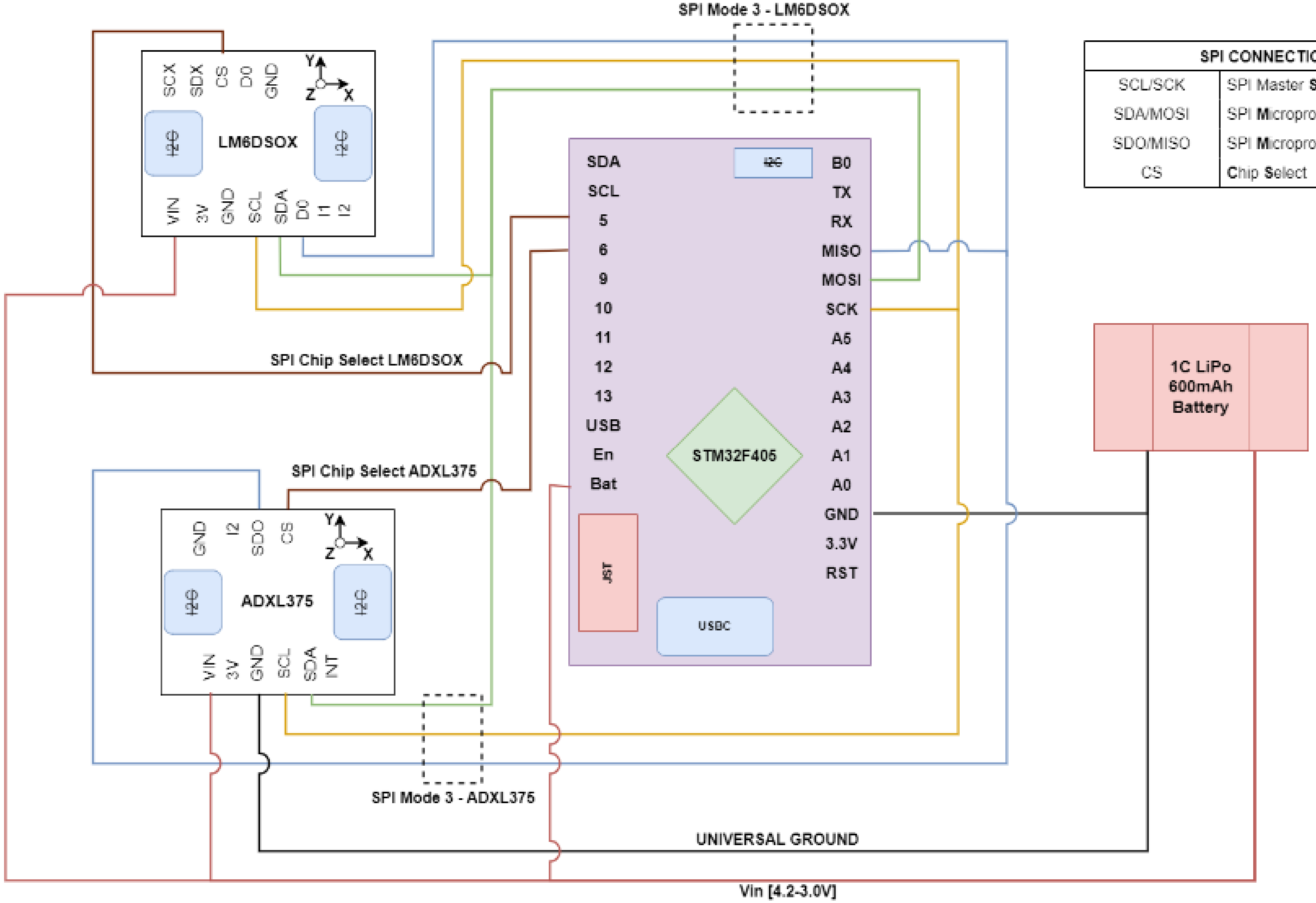
$$m * a_g = F$$

$$A * \tau = F$$

Component	Mass (g)	Force (N)	SA (mm²)
Featherboard	6.2	18	226.59
Accelerometer	0.5	1.5	137.76
IMU	1.7	5	137.76
Battery	15	44	N/A

Additional Analysis: Electronics

Wiring Diagram

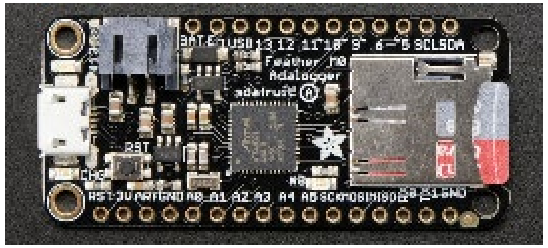


SPI CONNECTION DEFINITIONS	
SCL/SCK	SPI Master Serial Clock
SDA/MOSI	SPI Microprocessor Out Sensor In
SDO/MISO	SPI Microprocessor In Sensor Out
CS	Chip Select

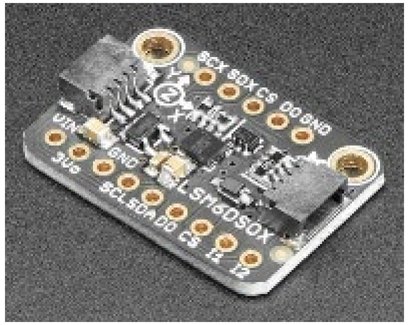
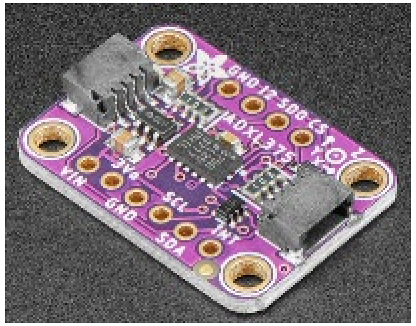
Sensing Hardware Summary

Microprocessor – Adafruit Featherlogger M0

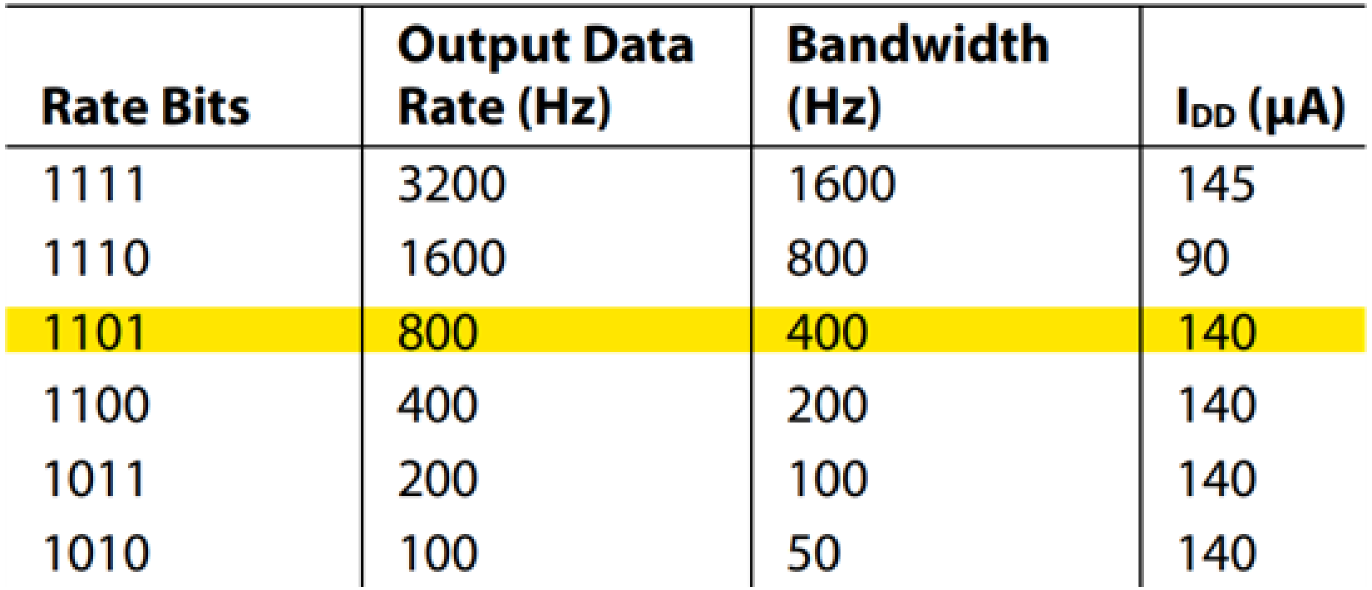
Parameter	Specification
Clock	48 MHz (maximum)
Power Consumption	6.3 mA @ 3.6V
Memory	256KB Onboard Flash + I2C SD Expansion 32KB RAM



Sensors

Parameter	LM6DSOX (IMU – 6 DOF)	ADXL375 (Accelerometer – 3 DOF)
Range [G]	±2/4/8/16	± 200 G
Sensitivity [µG/LSB]	61/122/244/488	49000
ODR [Hz] (maximum)	6666	800
Current Draw [mA]	0.55 @ 3.3V	0.14 @ 3.3V
Sensor Image		

Power References



Rate Bits	Output Data Rate (Hz)	Bandwidth (Hz)	I_{DD} (µA)
1111	3200	1600	145
1110	1600	800	90
1101	800	400	140
1100	400	200	140
1011	200	100	140
1010	100	50	140

Data Collection – High Range Accelerometer

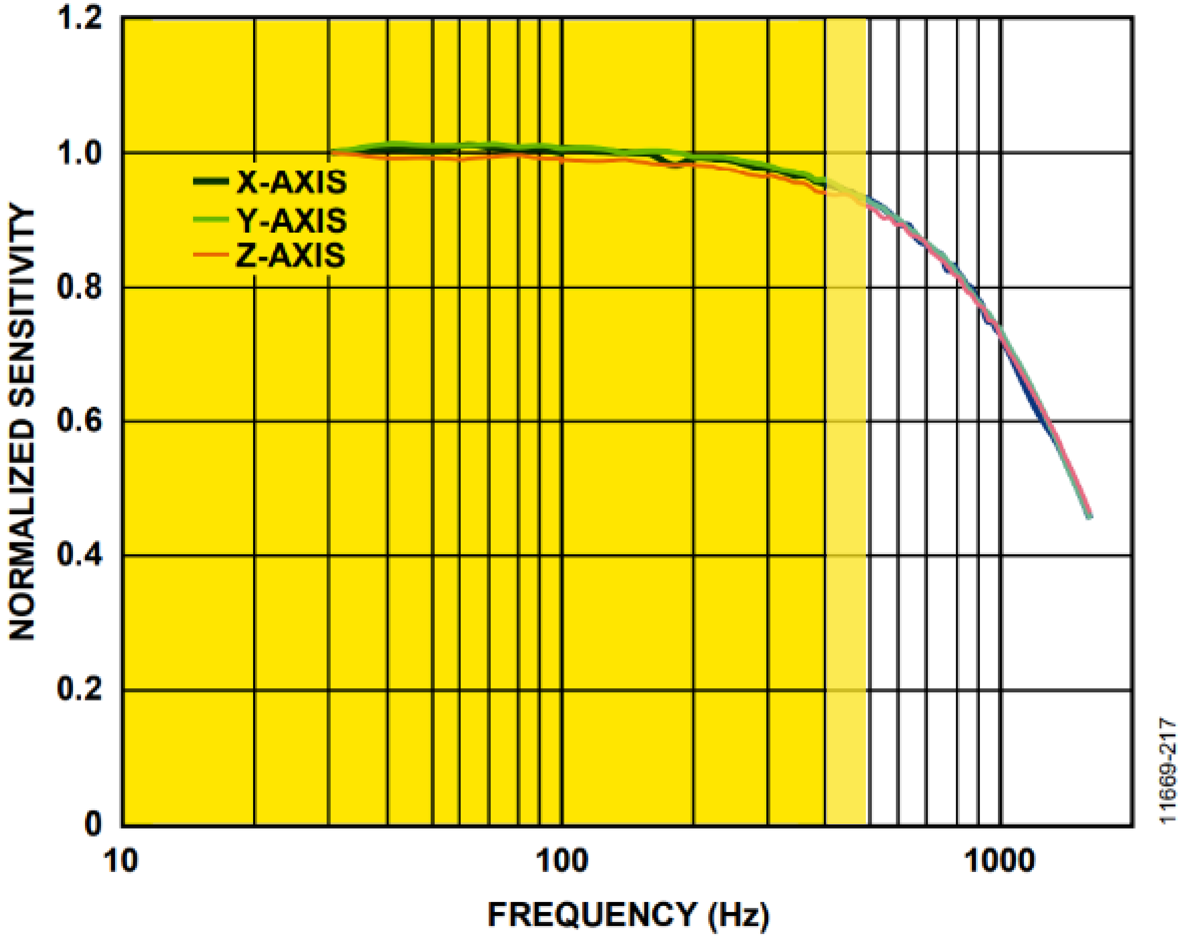
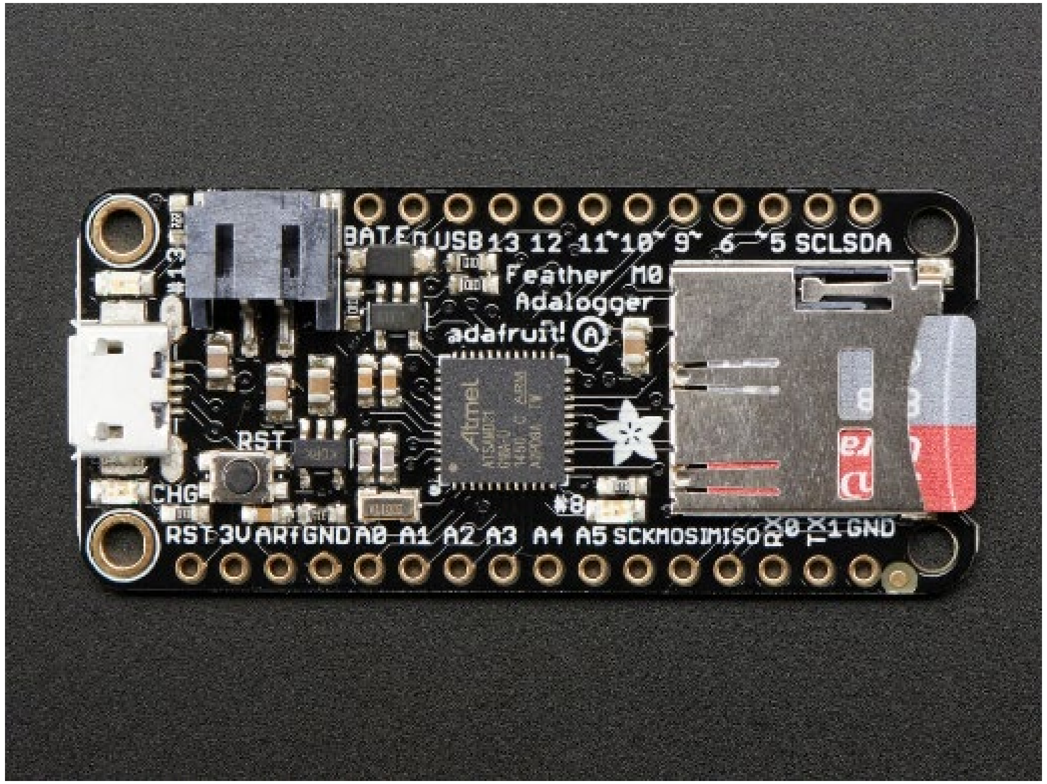


Figure 21. Frequency Response

Data Collection – Microprocessor

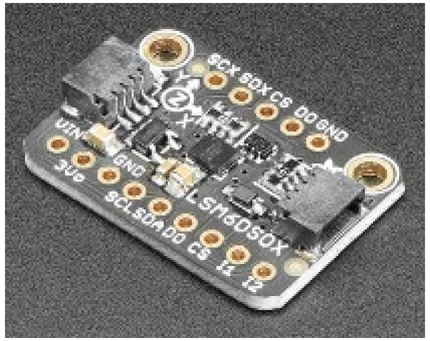
Parameter	Specification
Clock	48 MHz (maximum)
I/O	USB, I2C, SPI
DAC	10-bit
Power Consumption	6.3 mA @ 3.6V
Memory	256KB Onboard Flash + I2C SD Expansion 32KB RAM
Power Supply	500mA 3.3V Regulator 100mA LiPo Charger



Data Collection – High Bandwidth 6DOF

LM6DSOX

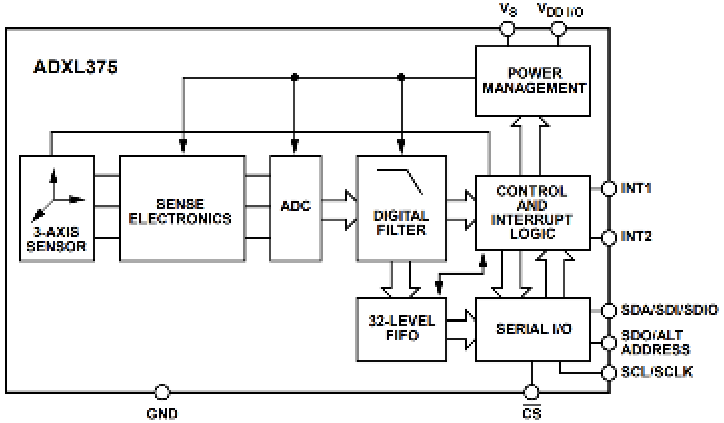
Parameter	**Specification**
DOF	6
Range	±2/4/8/16 G
Sensitivity	61/122/244/488 µG/LSB
ODR	6666 Hz (maximum)
Current Draw	0.55 mA (high-performance)

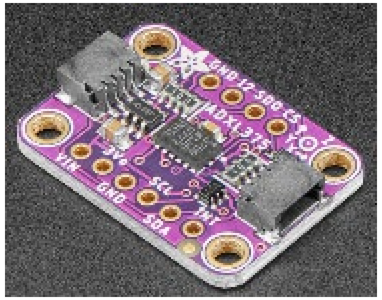


Data Collection – High Range Accelerometer

ADXL375

Parameter	Specification
DOF	3
Range	± 200 G
Sensitivity	49 mG/LSB
ODR	800 Hz
Current Draw	0.14 mA (maximum)



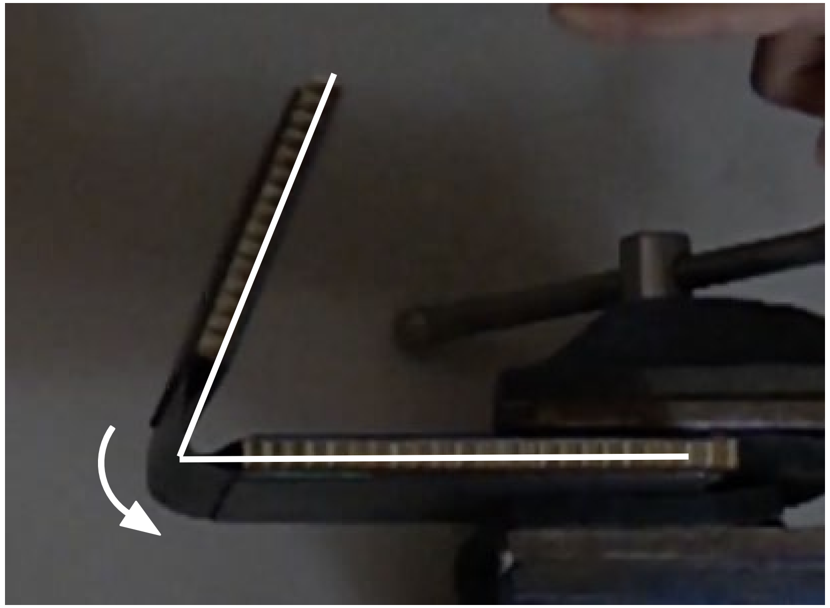


Additional Analysis: G-Loading

G-Load Prediction Method 1: Observation

- Highest acceleration is instant of release.
- Solved for ω at several θ ’s, given $\theta_0 = 0$.

$$\theta = \omega t + \theta_0 \longrightarrow \omega = \theta / t$$



- Used highest calculated ω, solved for a.

$$\omega = \alpha t = at/r \longrightarrow a = \omega r/t$$

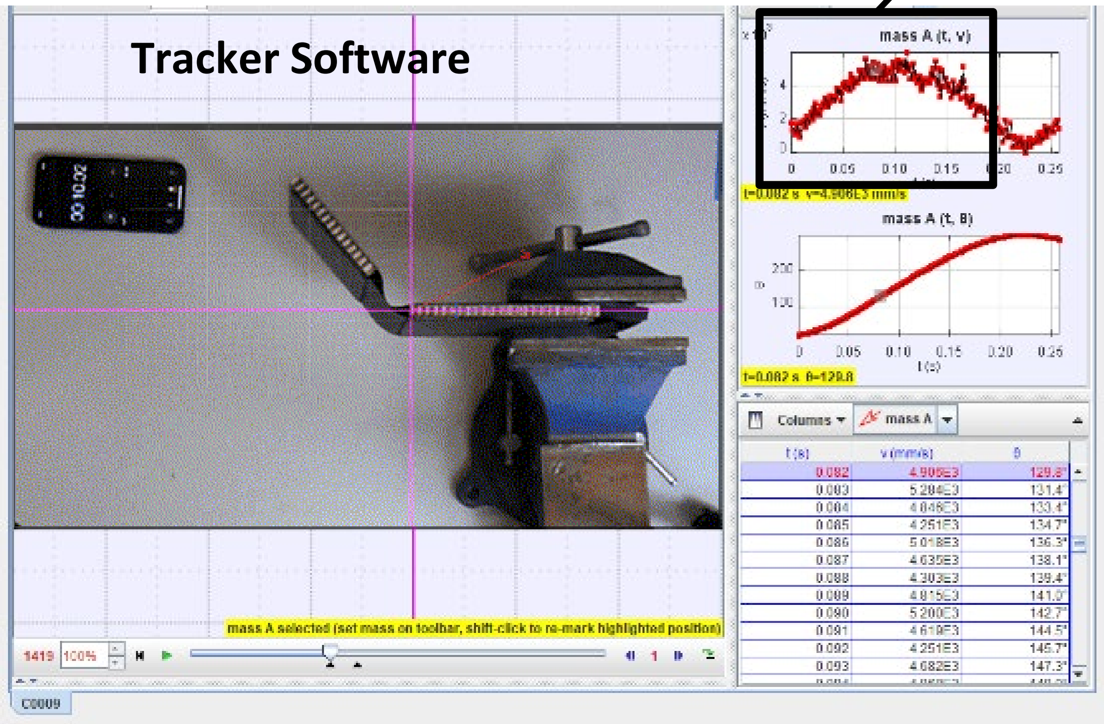
- Predicted max g-load: **10.4 Gs [102 m/s²]**

Method 2: Motion Capture Software "Tracker"

- Linear regression line through first 24 milliseconds.
- Predicted max g-load: **7.33 Gs [71.9 m/s²]**

$$v = at + v_0$$

$$v = (71.9)t + (0.836)$$

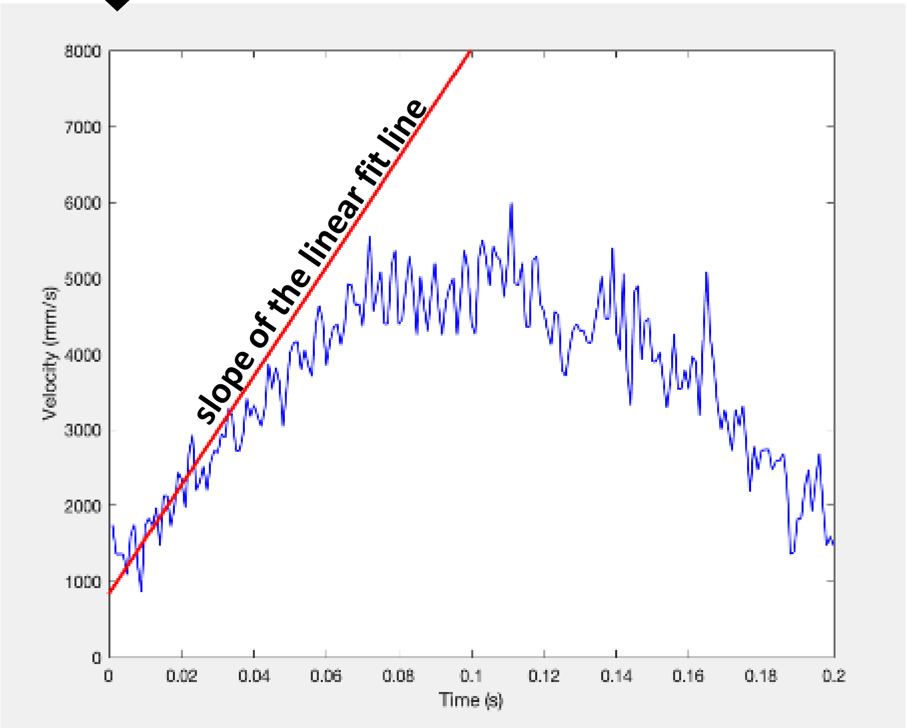


t=0.082 s v=4.906E3 mm/s

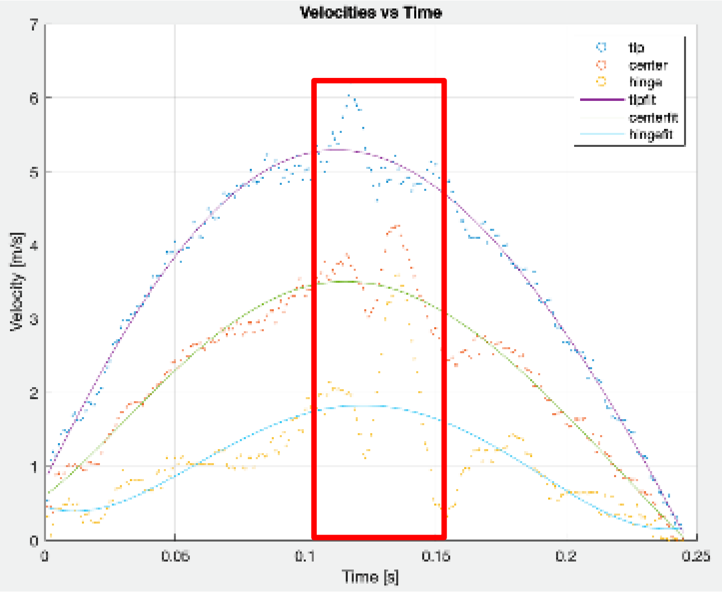
t=0.082 s θ=129.8

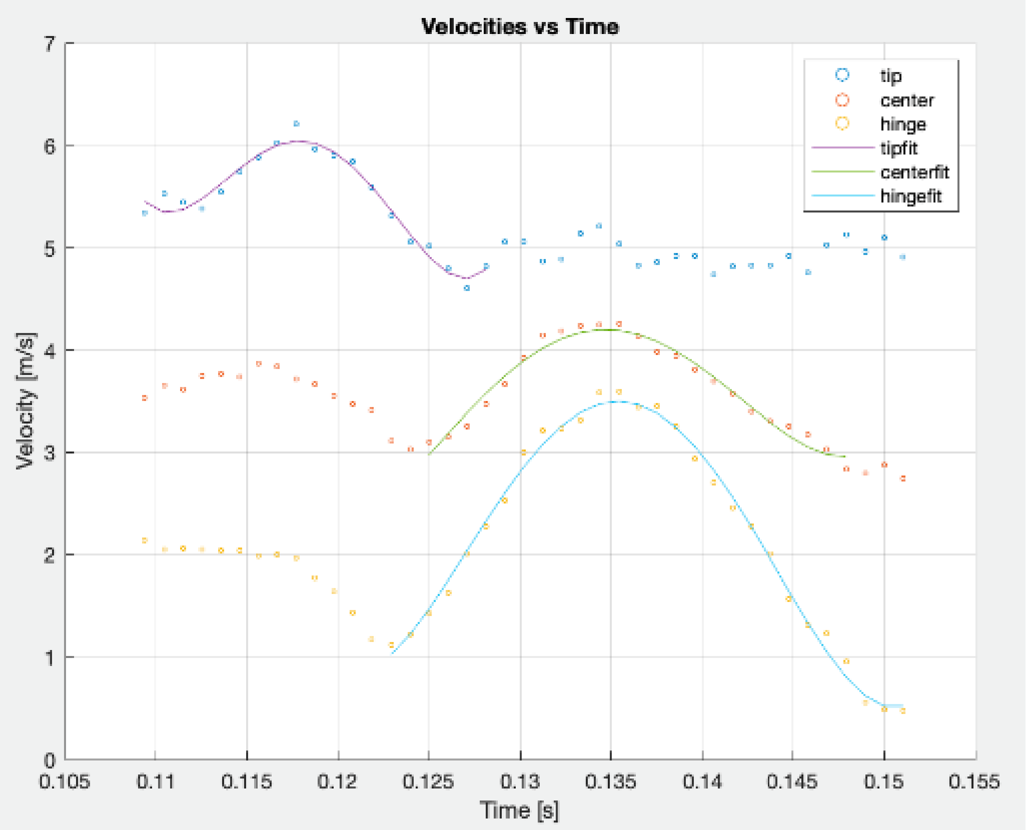
t (s)	v (mm/s)	θ
0.082	4.906E3	129.8°
0.083	5.284E3	131.4°
0.084	4.046E3	133.4°
0.085	4.251E3	134.7°
0.086	5.018E3	136.3°
0.087	4.635E3	138.1°
0.088	4.303E3	139.4°
0.089	4.815E3	141.0°
0.090	5.200E3	142.7°
0.091	4.619E3	144.5°
0.092	4.251E3	145.7°
0.093	4.682E3	147.3°

mass A selected (set mass on toolbar, shift-click to re-mark highlighted position)



Method 3: Motion Capture w/ Reflective Tape

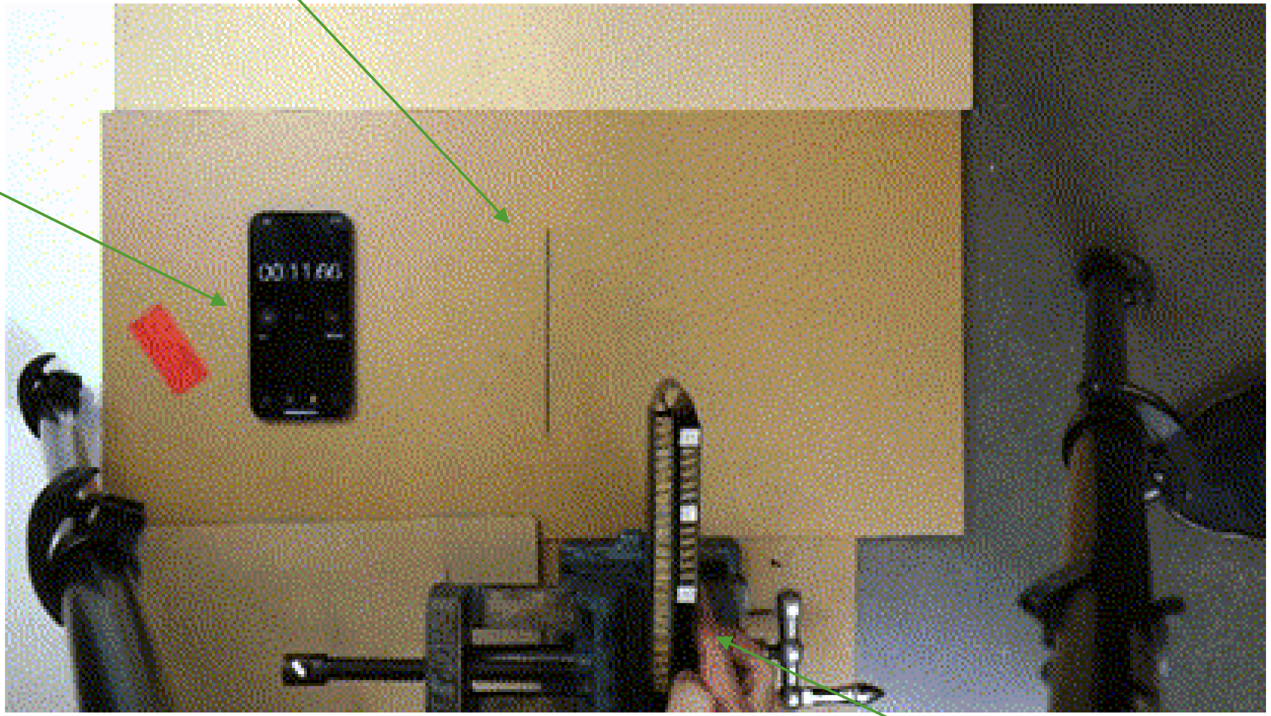




Predicted Max G-load: **30.75**

@ θ ≅ 180°

Optical Tracking



Scale

Timer

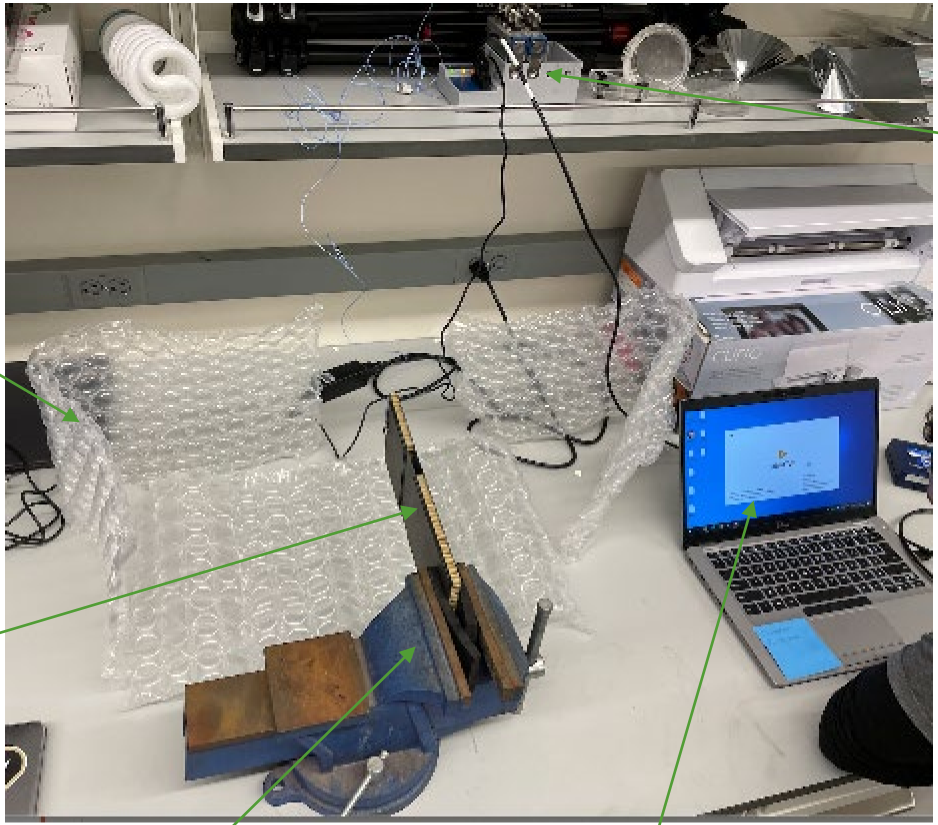
Vice Grip

External Lighting

Camera

Tri-pod

Teardrop Accelerometer Testing



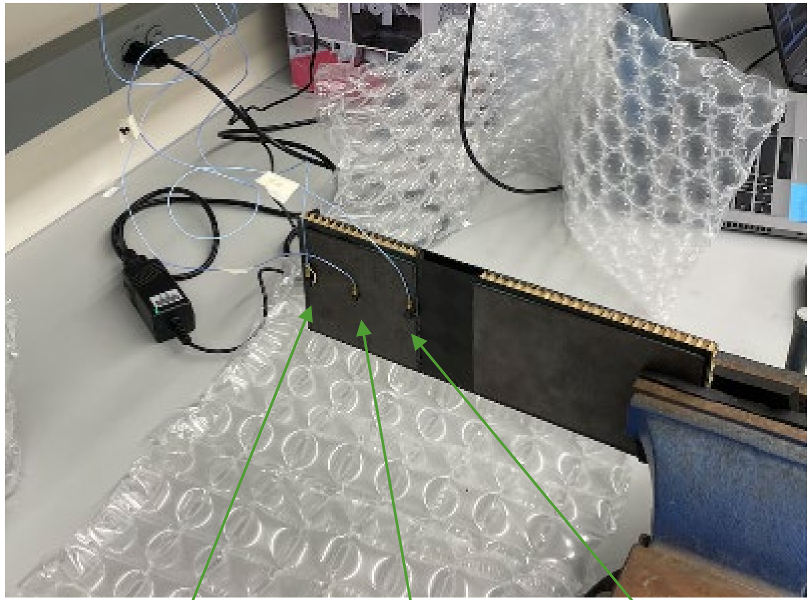
LabVIEW DAQ

Bubble Wrap Protection

Panel

Vice

LabVIEW Program



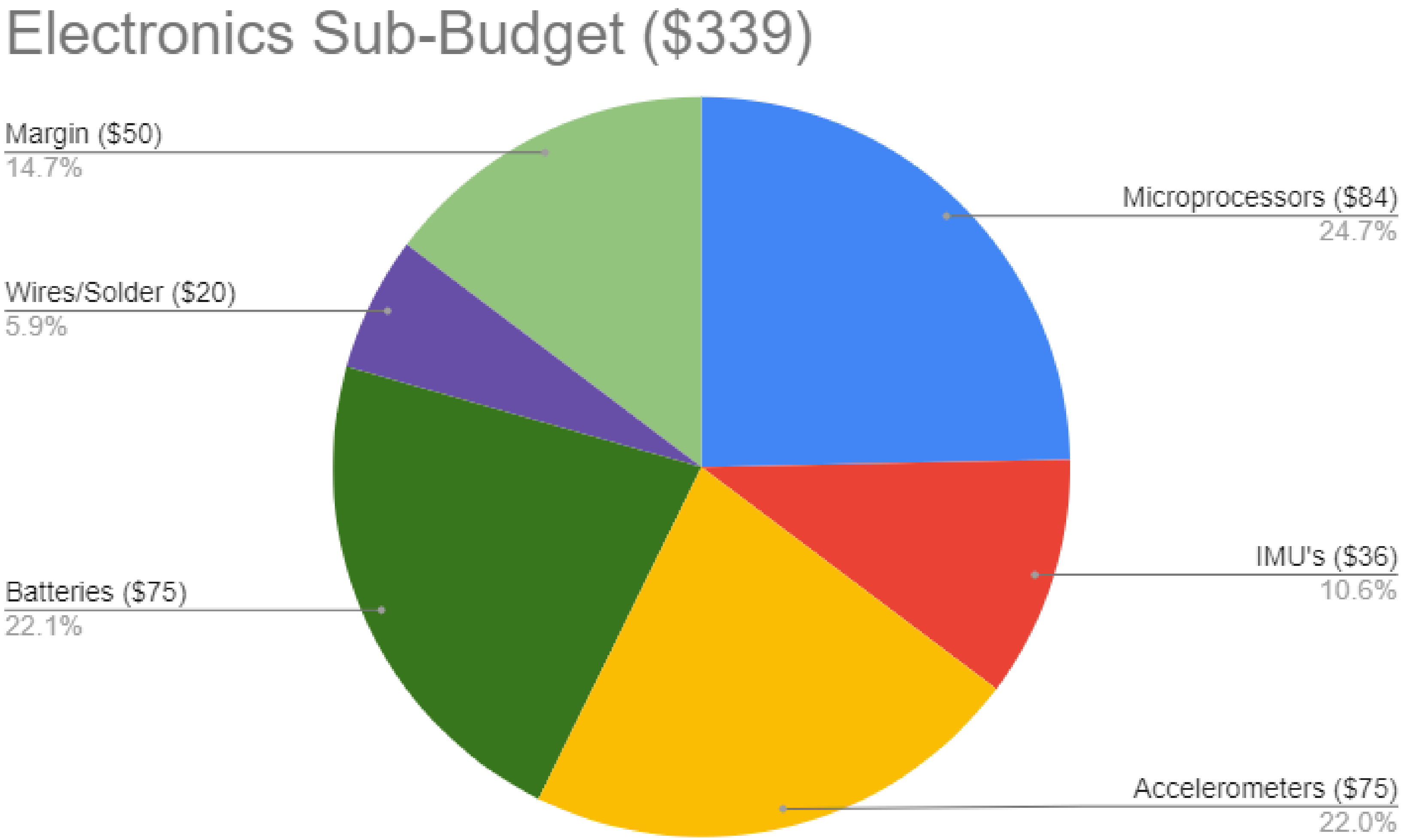
Teardrop 0 (tip)

Teardrop 1 (center)

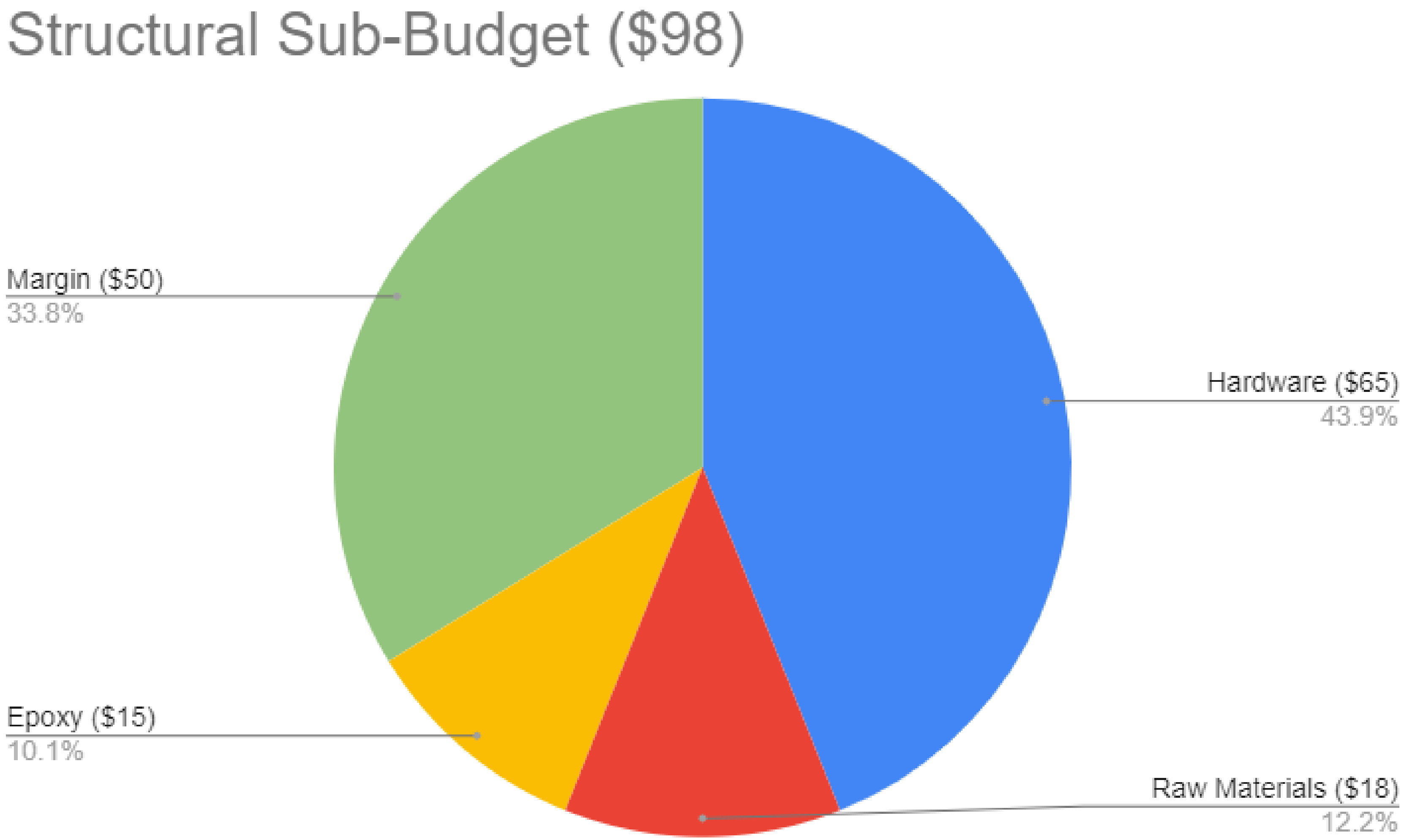
Teardrop 2 (hinge)

Cost Plan Breakdown

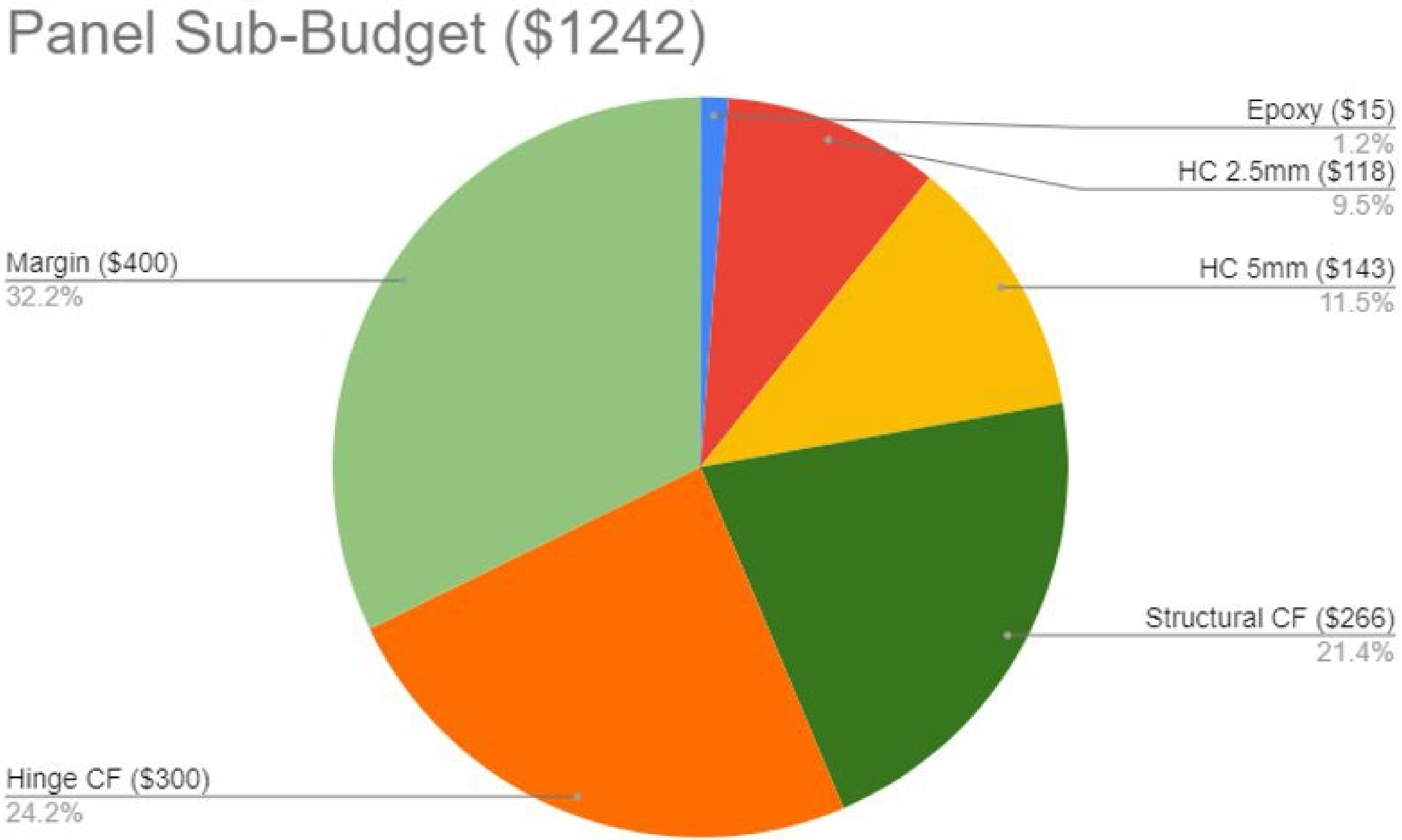
Electronics



Structural

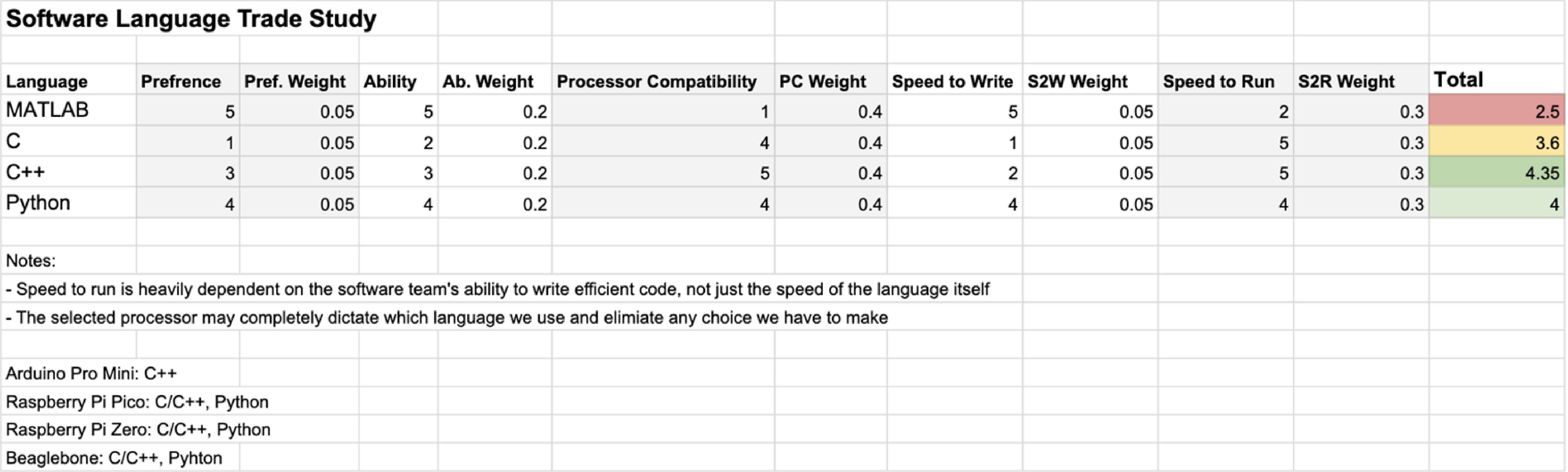

Structural Sub-Budget ($98)
Margin ($50)
33.8%
Hardware ($65)
43.9%
Epoxy ($15)
10.1%
Raw Materials ($18)
12.2%

Panel


Panel Sub-Budget ($1242)
Epoxy ($15)
1.2%
HC 2.5mm ($118)
9.5%
HC 5mm ($143)
11.5%
Structural CF ($266)
21.4%
Hinge CF ($300)
24.2%
Margin ($400)
32.2%

PDR Trade Studies

Coding Language Trade Study Matrix



Software Language Trade Study

Language	**Prefrence**	**Pref. Weight**	**Ability**	**Ab. Weight**	**Processor Compatibility**	**PC Weight**	**Speed to Write**	**S2W Weight**	**Speed to Run**	**S2R Weight**	**Total**
MATLAB	5	0.05	5	0.2	1	0.4	5	0.05	2	0.3	2.5
C	1	0.05	2	0.2	4	0.4	1	0.05	5	0.3	3.6
C++	3	0.05	3	0.2	5	0.4	2	0.05	5	0.3	4.35
Python	4	0.05	4	0.2	4	0.4	4	0.05	4	0.3	4

Notes:

- Speed to run is heavily dependent on the software team's ability to write efficient code, not just the speed of the language itself
- The selected processor may completely dictate which language we use and elimiate any choice we have to make

Arduino Pro Mini: C++
Raspberry Pi Pico: C/C++, Python
Raspberry Pi Zero: C/C++, Python
Beaglebone: C/C++, Pyhton

Processing Trade Study

Metric	**Description**	**Weight**	**Requirement**
User interface	Ease of use (sufficient documentation)	0.2	D1.1
Mass	Weight of the microcontroller/microprocessor	0.1	FR2, D2.2
Power consumption	Current draw at nominal voltage	0.3	FR5, D5.1
Processing speed	Maximum clock frequency & computational efficiency estimate	0.25	D1.1
Dimensions	Size of the microcontroller/microprocessor	0.1	FR2, D2.1
Cost	Price and lead time	0.05	FR3, D3.2

Metric	**Arduino Pro Micro**	**Teensy 4.1**	**RPi Pico**	**RPi Zero 2W**	**Feather 32u4**
User interface (0.2)	3	4	2	2	4
Mass (0.1)	4	3	5	3	5
Power consumption (0.3)	5	3	1	0	5
Processing speed (0.25)	2	4	3	5	2
Dimensions (0.1)	2	2	5	3	1
Cost (0.05)	4	4	4	3	4
TOTAL =	3.4	3.4	2.65	2.4	3.6

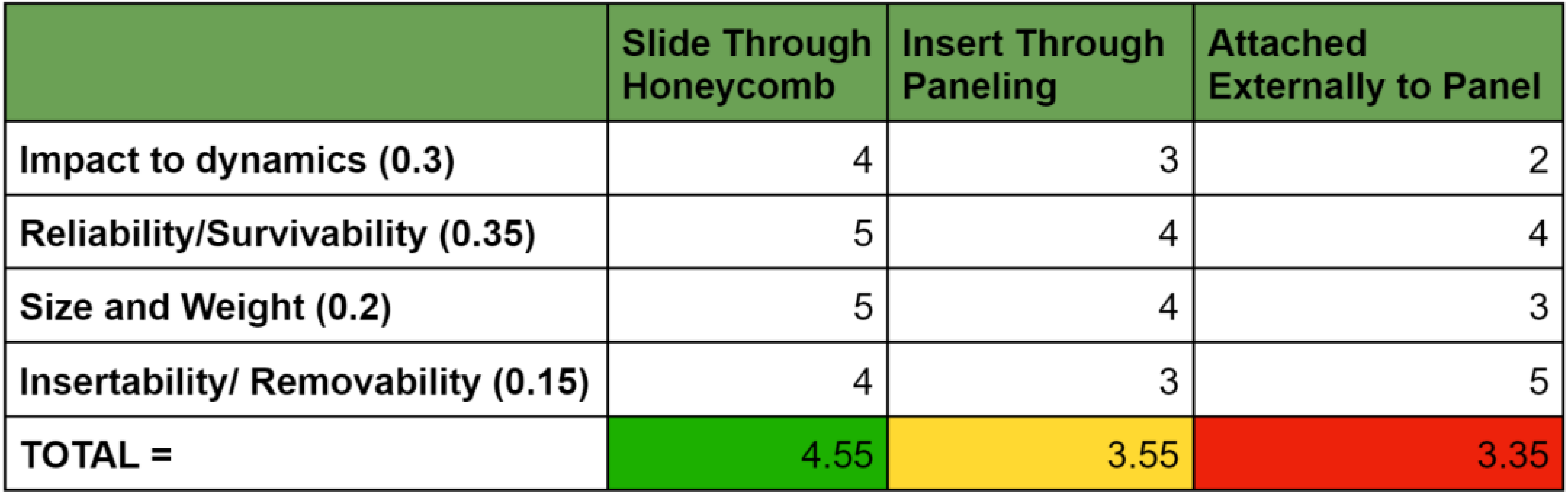
Sensor Trade Study

Metric	**Description**	**Weight**
Sensing capabilities	Amount of Gs the sensor is capable of sensing	0.2
Shock survivability	Amount of G's the sensor can withstand before breaking	0.01
Dimensions	Dimensions of the sensor	0.1
Mass	Weight of the sensor	0.08
Microcontroller/microprocessor interface	Type of communication to/from sensor (Digital vs. Analog)	0.08
Axis	Amount of axis the sensor is capable of sensing	0.2
Ease of attachment	How easy the sensor is to mount to a PCB board	0.05
Voltage range	Range of input voltage the sensor needs for functioning	0.1
Output data rates range	Range of the speed of obtaining output data	0.1
User interface	Ease of use (sufficient documentation)	0.08

Suite Insertion/Connection Trade Study

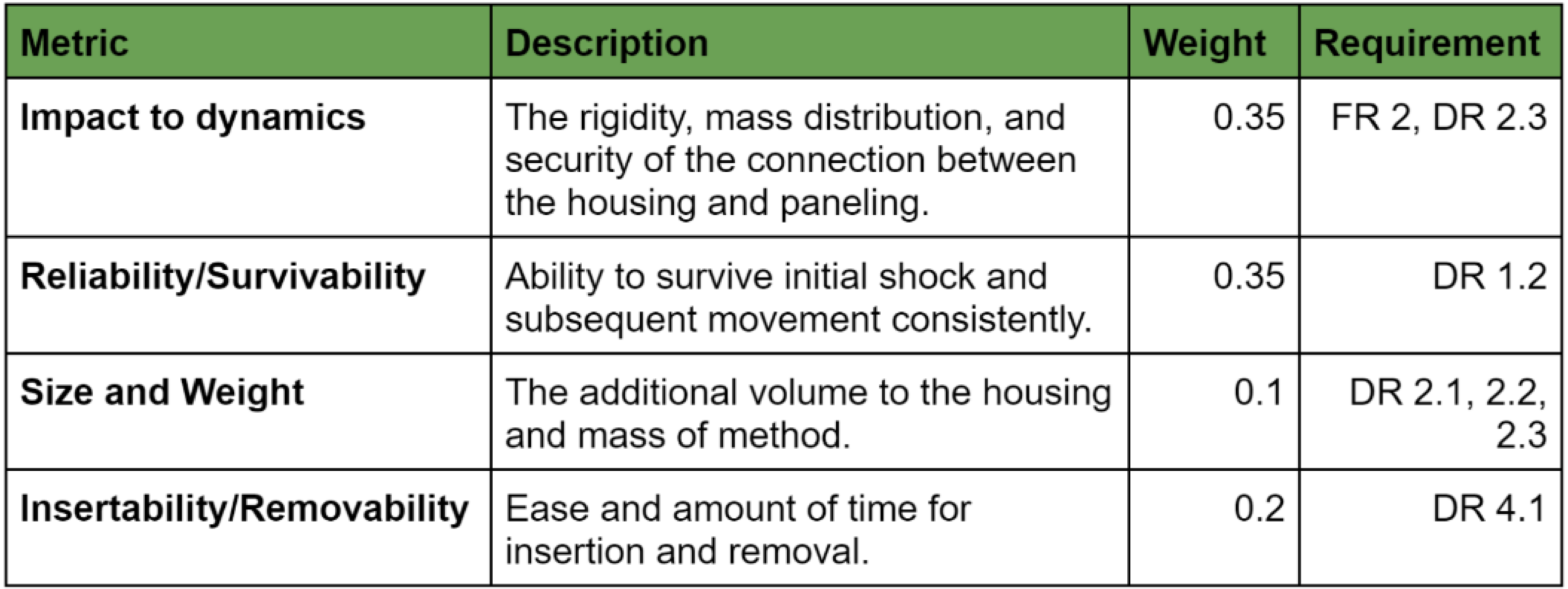
Metric	Description	Weight	Requirement
Impact to dynamics	The rigidity, mass distribution, and security of the placement of the housing on the paneling.	0.3	FR 2, DR 2.3
Reliability/Survivability	Ability to survive initial shock and subsequent movement consistently.	0.35	DR 1.2
Size and Weight	The dimensions and the total mass of the structure.	0.2	DR 2.1, 2.2, 2.3
Insertability/Removability	Ease and amount of time for insertion and removal.	0.15	DR 4.1

Suite Insertion/Connection Trade Study



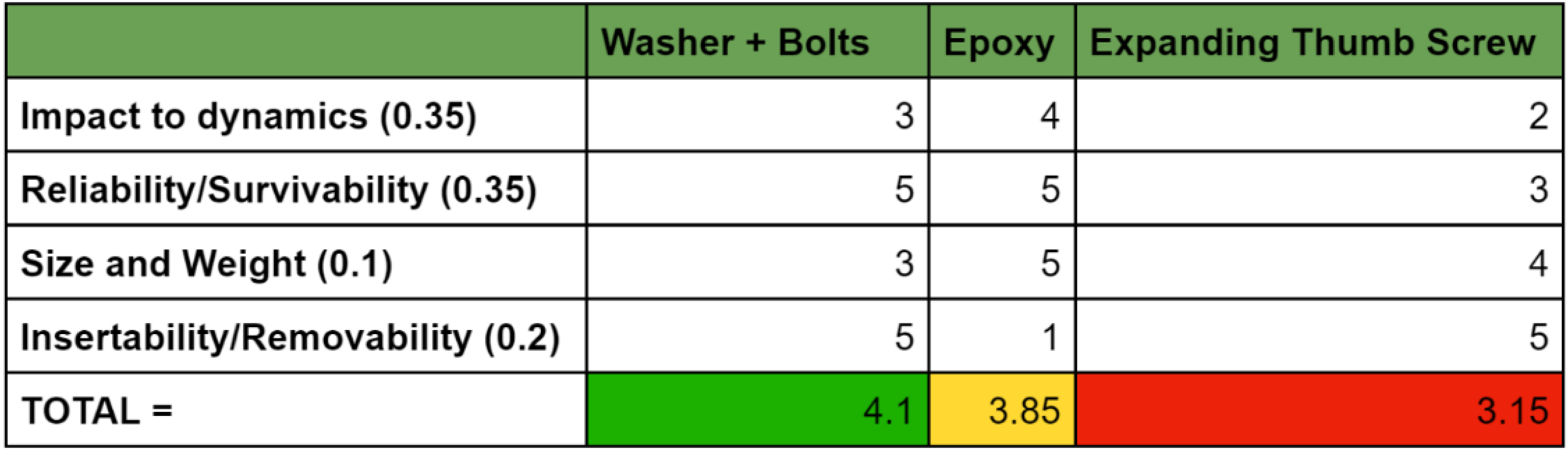
	Slide Through Honeycomb	Insert Through Paneling	Attached Externally to Panel
Impact to dynamics (0.3)	4	3	2
Reliability/Survivability (0.35)	5	4	4
Size and Weight (0.2)	5	4	3
Insertability/ Removability (0.15)	4	3	5
TOTAL =	4.55	3.55	3.35

Housing Attachment Trade Study



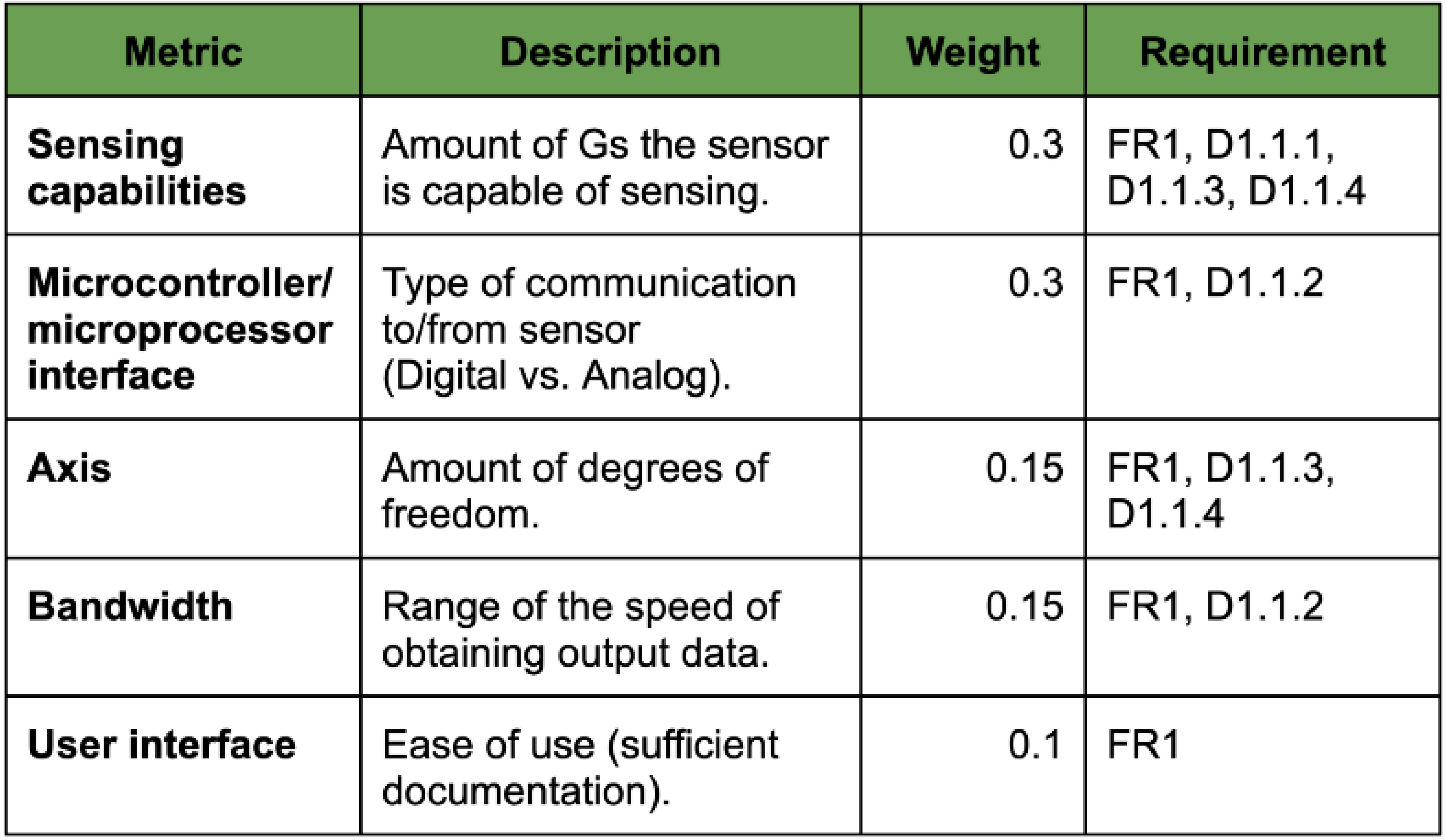
Metric	Description	Weight	Requirement
Impact to dynamics	The rigidity, mass distribution, and security of the connection between the housing and paneling.	0.35	FR 2, DR 2.3
Reliability/Survivability	Ability to survive initial shock and subsequent movement consistently.	0.35	DR 1.2
Size and Weight	The additional volume to the housing and mass of method.	0.1	DR 2.1, 2.2, 2.3
Insertability/Removability	Ease and amount of time for insertion and removal.	0.2	DR 4.1

Housing Attachment Trade Study



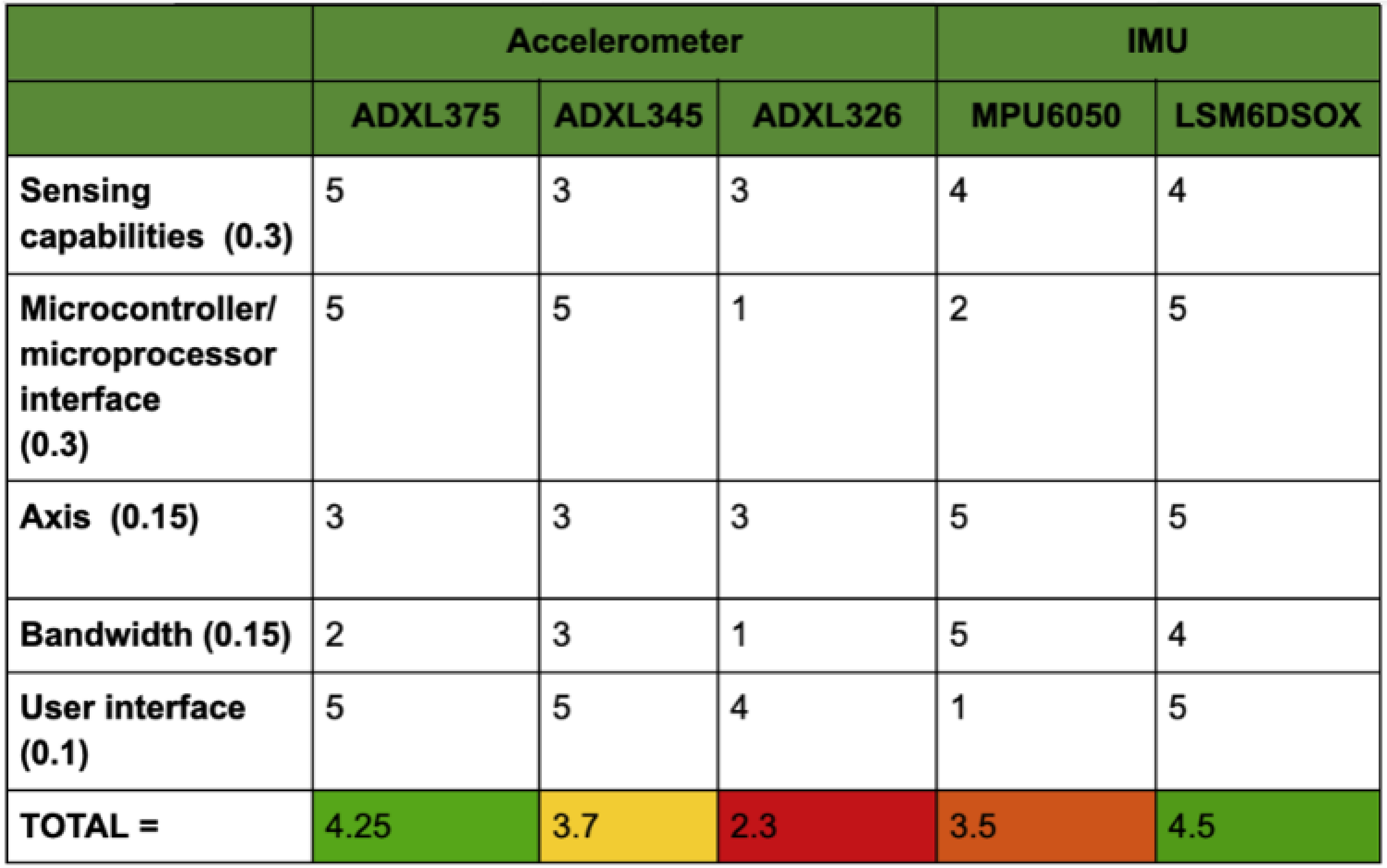
	Washer + Bolts	Epoxy	Expanding Thumb Screw
Impact to dynamics (0.35)	3	4	2
Reliability/Survivability (0.35)	5	5	3
Size and Weight (0.1)	3	5	4
Insertability/Removability (0.2)	5	1	5
TOTAL =	🟩 4.1	🟨 3.85	🟥 3.15

Sensor Trade Study



Metric	Description	Weight	Requirement
Sensing capabilities	Amount of Gs the sensor is capable of sensing.	0.3	FR1, D1.1.1, D1.1.3, D1.1.4
Microcontroller/ microprocessor interface	Type of communication to/from sensor (Digital vs. Analog).	0.3	FR1, D1.1.2
Axis	Amount of degrees of freedom.	0.15	FR1, D1.1.3, D1.1.4
Bandwidth	Range of the speed of obtaining output data.	0.15	FR1, D1.1.2
User interface	Ease of use (sufficient documentation).	0.1	FR1

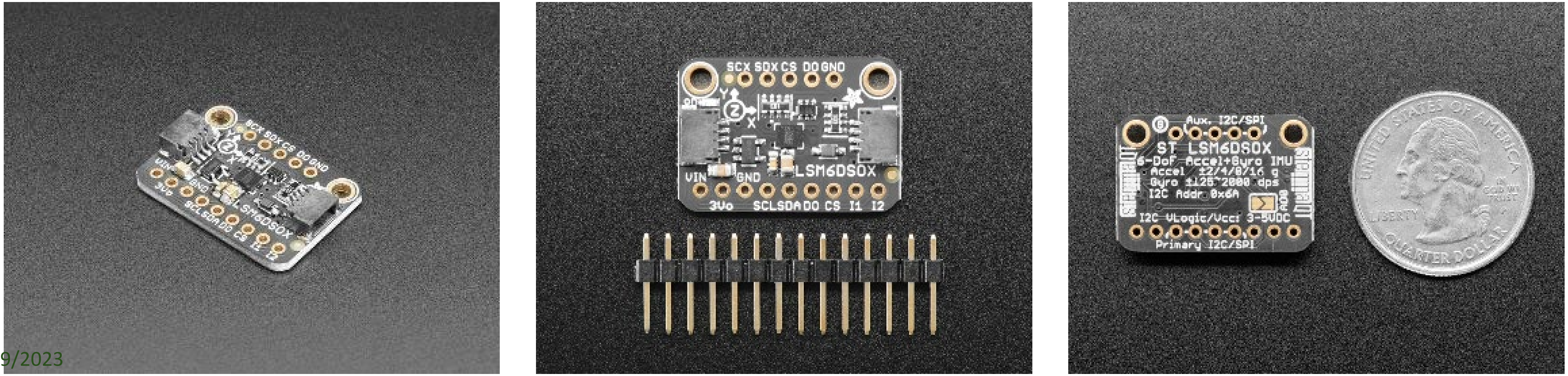
Sensor Trade Study



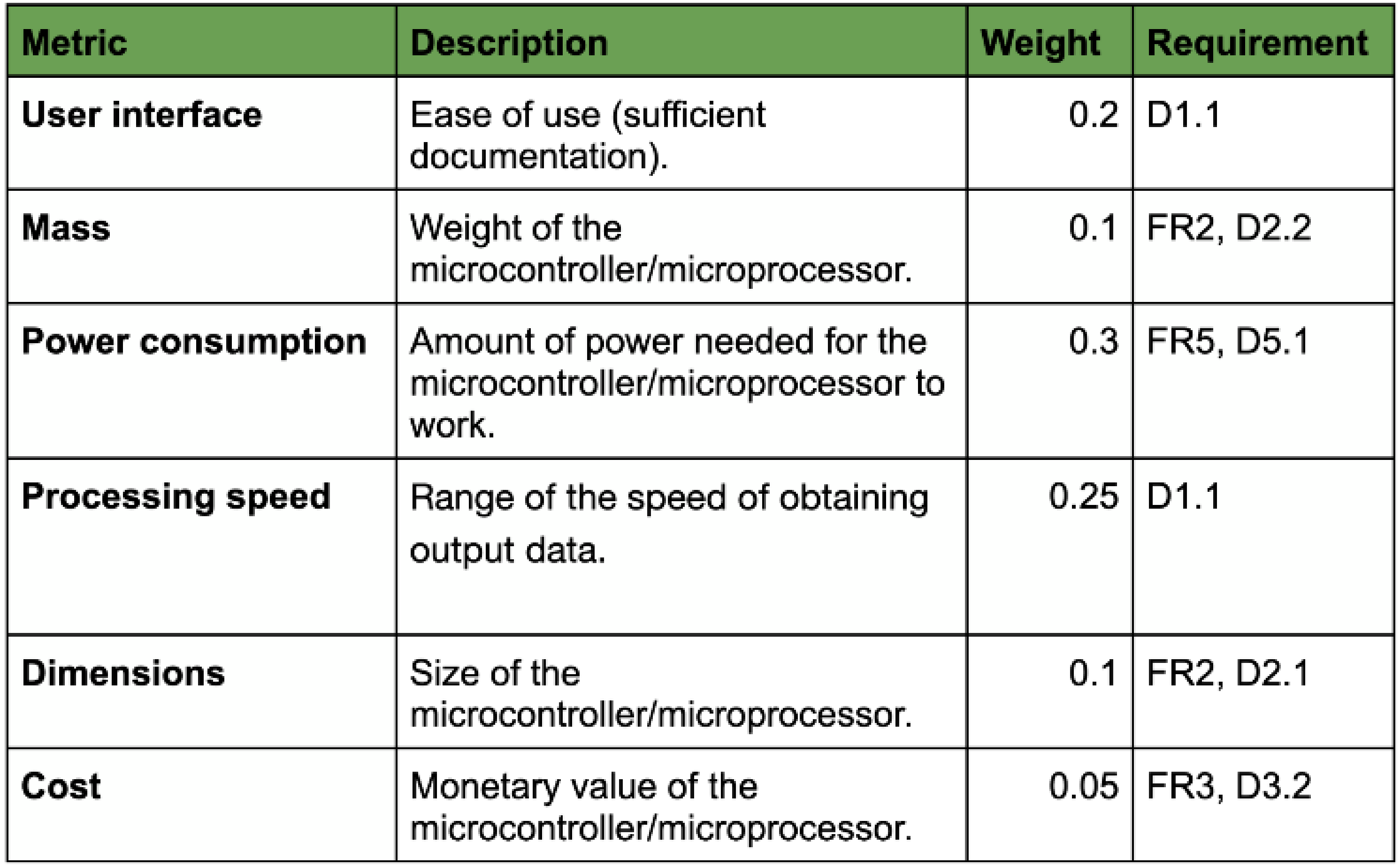
	Accelerometer			IMU	
	ADXL375	ADXL345	ADXL326	MPU6050	LSM6DSOX
Sensing capabilities (0.3)	5	3	3	4	4
Microcontroller/ microprocessor interface (0.3)	5	5	1	2	5
Axis (0.15)	3	3	3	5	5
Bandwidth (0.15)	2	3	1	5	4
User interface (0.1)	5	5	4	1	5
TOTAL =	4.25	3.7	2.3	3.5	4.5

Sensor Design Selection

	Dimension [mm]	Weight [g]	Degrees of Freedom	Interface	Sensing capabilities [Gs]	Voltage Range [V]	Shock Capabilities [Gs]	Bandwidth [kHz]
LSM6DSOX	25.6 x 17.8 x 4.6	1.7	6	SPI/I2C	2,4,6,8,16	3-5	10,000	1.6-6.7



Microcontroller/Microprocessor Trade Study



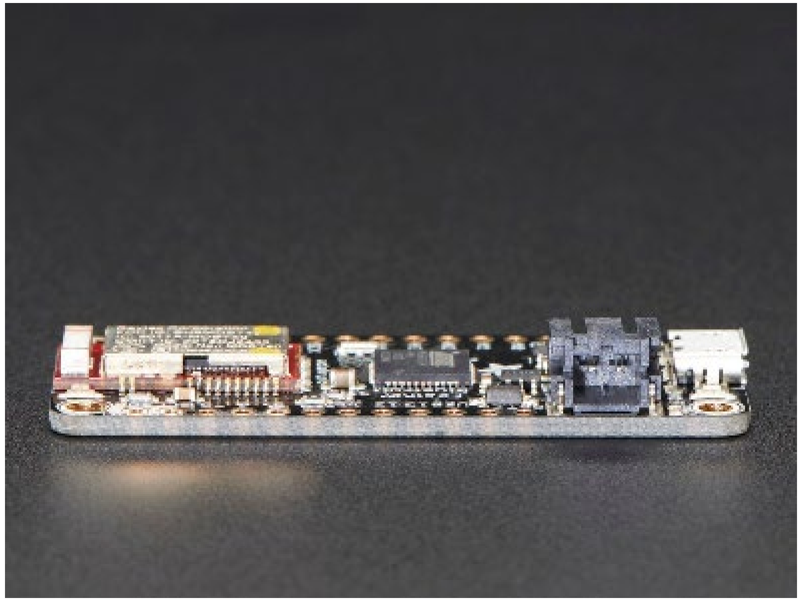
Metric	Description	Weight	Requirement
User interface	Ease of use (sufficient documentation).	0.2	D1.1
Mass	Weight of the microcontroller/microprocessor.	0.1	FR2, D2.2
Power consumption	Amount of power needed for the microcontroller/microprocessor to work.	0.3	FR5, D5.1
Processing speed	Range of the speed of obtaining output data.	0.25	D1.1
Dimensions	Size of the microcontroller/microprocessor.	0.1	FR2, D2.1
Cost	Monetary value of the microcontroller/microprocessor.	0.05	FR3, D3.2

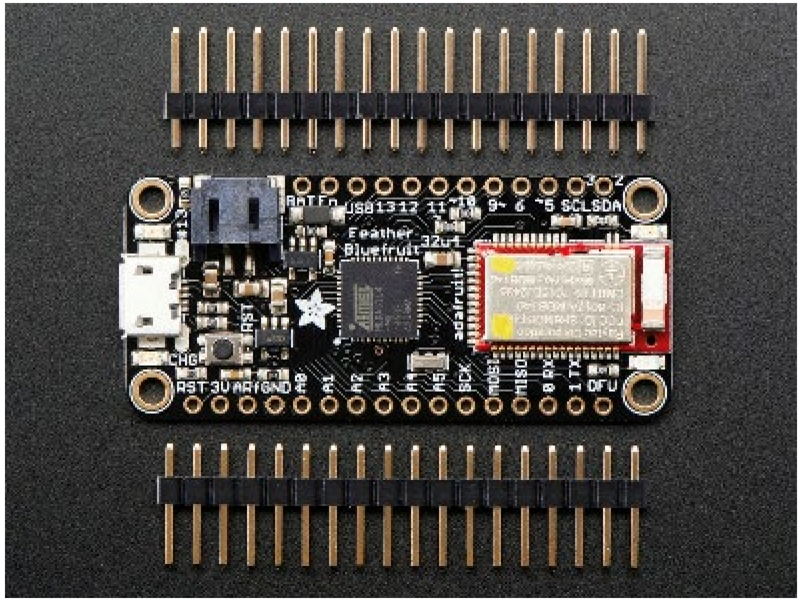
Microcontroller/Microprocessor Trade Study

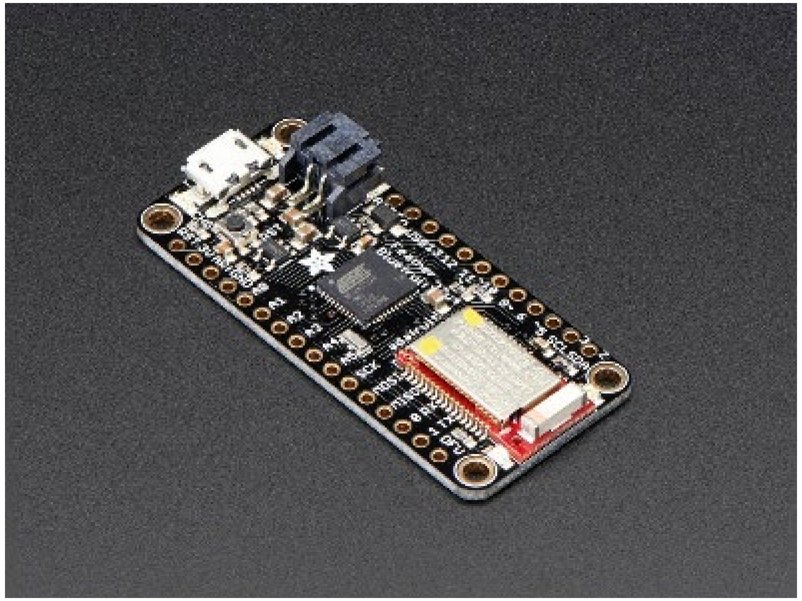
Metric	Arduino Pro Micro	Teensy 4.1	RPi Pico	RPi Zero 2W	Feather 32u4
User interface (0.2)	3	4	2	2	4
Mass (0.1)	4	3	5	3	5
Power consumption (0.3)	5	3	1	1	5
Processing speed (0.25)	2	4	3	5	2
Dimensions (0.1)	2	2	5	3	1
Cost (0.05)	4	4	4	3	4
TOTAL =	3.4	3.4	2.65	2.7	3.6

Microcontroller Design Selection

	Dimension [mm]	Weight [g]	Power Consumption [mA]	Processing Speed [MHz]	Cost
Feather 32u4	51 x 23 x 8	5.7	~10	8	$25







Linked Sources

Materials:

- Honeycomb Core
- Outer Carbon Fiber
- Cyanoacrylate