Critical Design Review

Lockheed Martin LLAMAS Team

sateLLite ADCS fault MAnagement System

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Corwin Sheahan
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	2.2 – MockSat	*Zack T.*
	2.3 – Software	*Pol S.*
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	3.1 – CDH	
	3.2 – Fault Injection and Management	
	3.3 – Pointing Accuracy	
4.0	Design Requirements and their Satisfaction (DR&S)	
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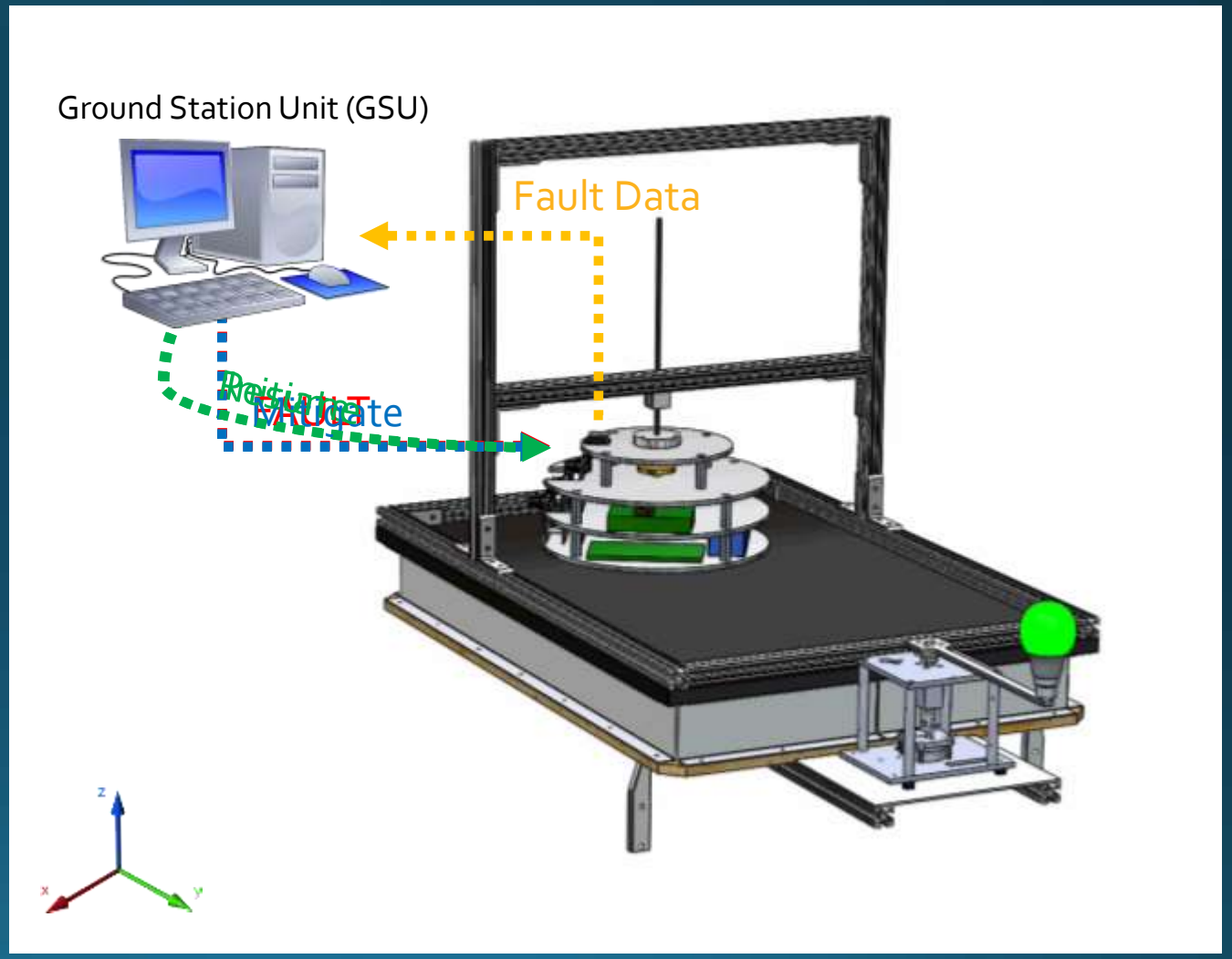
6.0	Management Items	*Sam O.*
7.0	Q & A	*LLAMAS*

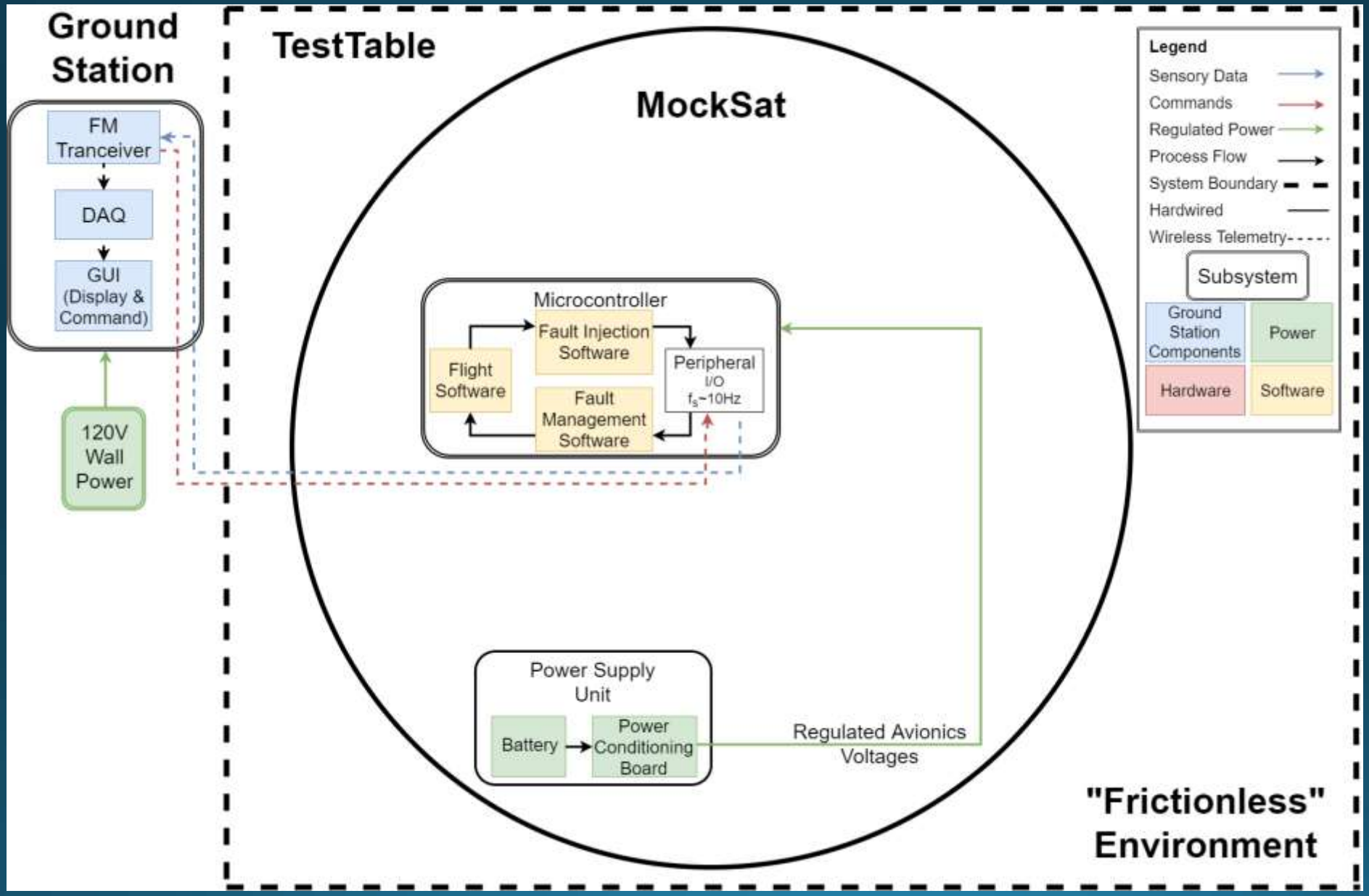
Concept Of Operations (CONOPs)

- Test Initiation
  - MockSat initializes and begins searching for target.
- Nominal Operation
  - MockSat has acquired target and tracks motion to within ±2.5°.
- Faulted
  - Fault Injection has introduced a fault that inhibits the MockSat from tracking the target.
- Management of Fault
  - Fault Management has detected and identified the fault and relayed that information to the Ground Station Unit.
  - MockSat is in a faulted state and not maintaining any attitude.
- Initiation of Recovery Sequence
  - MockSat has regained attitude control and is awaiting command to resume searching.
- Recovering
  - MockSat has received command to resume searching for target.
- Return to Nominal Operation
  - Target has re-acquired the target and is tracking to within ±2.5°.



CONOPS (10x speed)

Functional Block Diagram (FBD)



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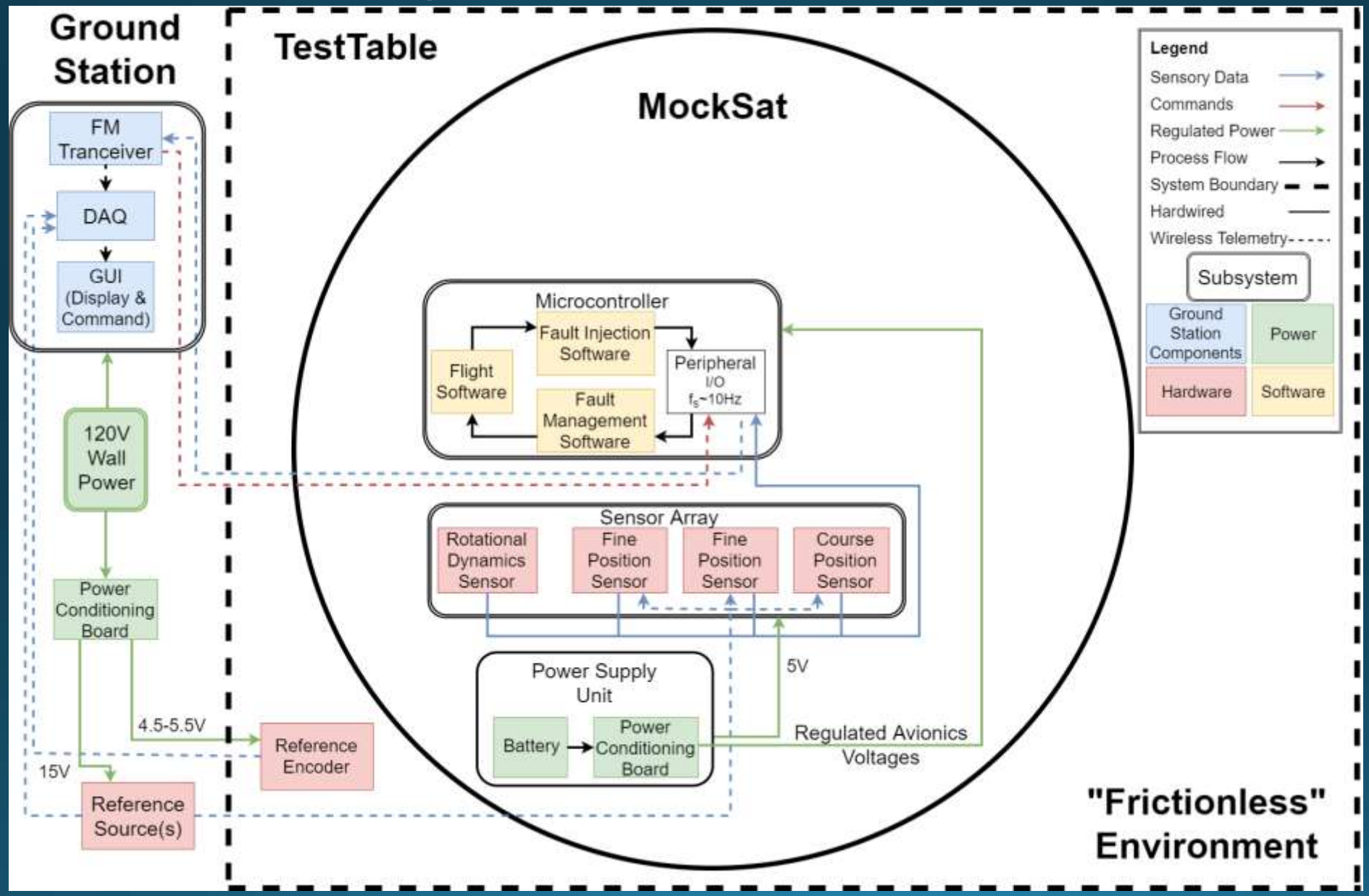

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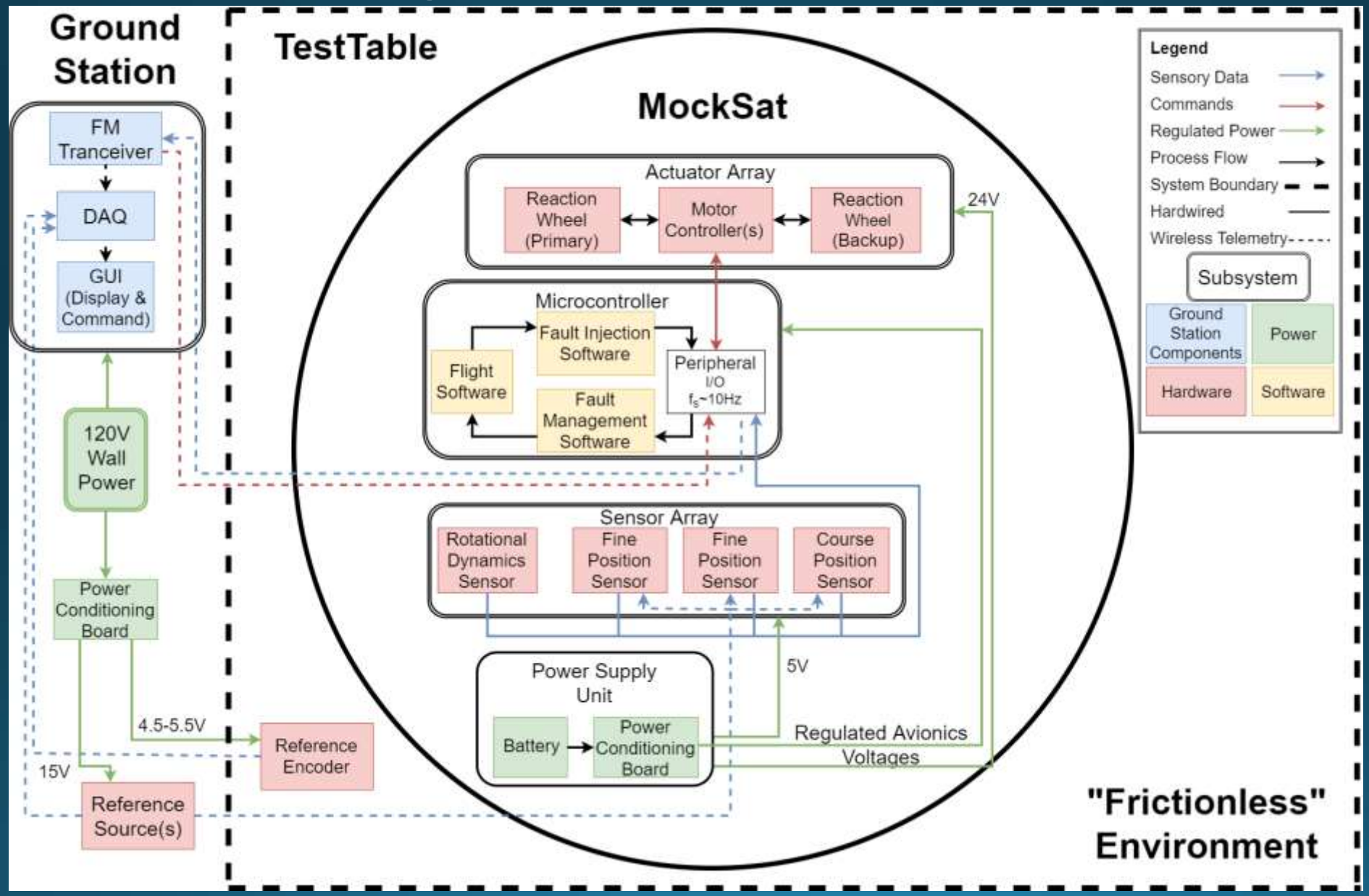

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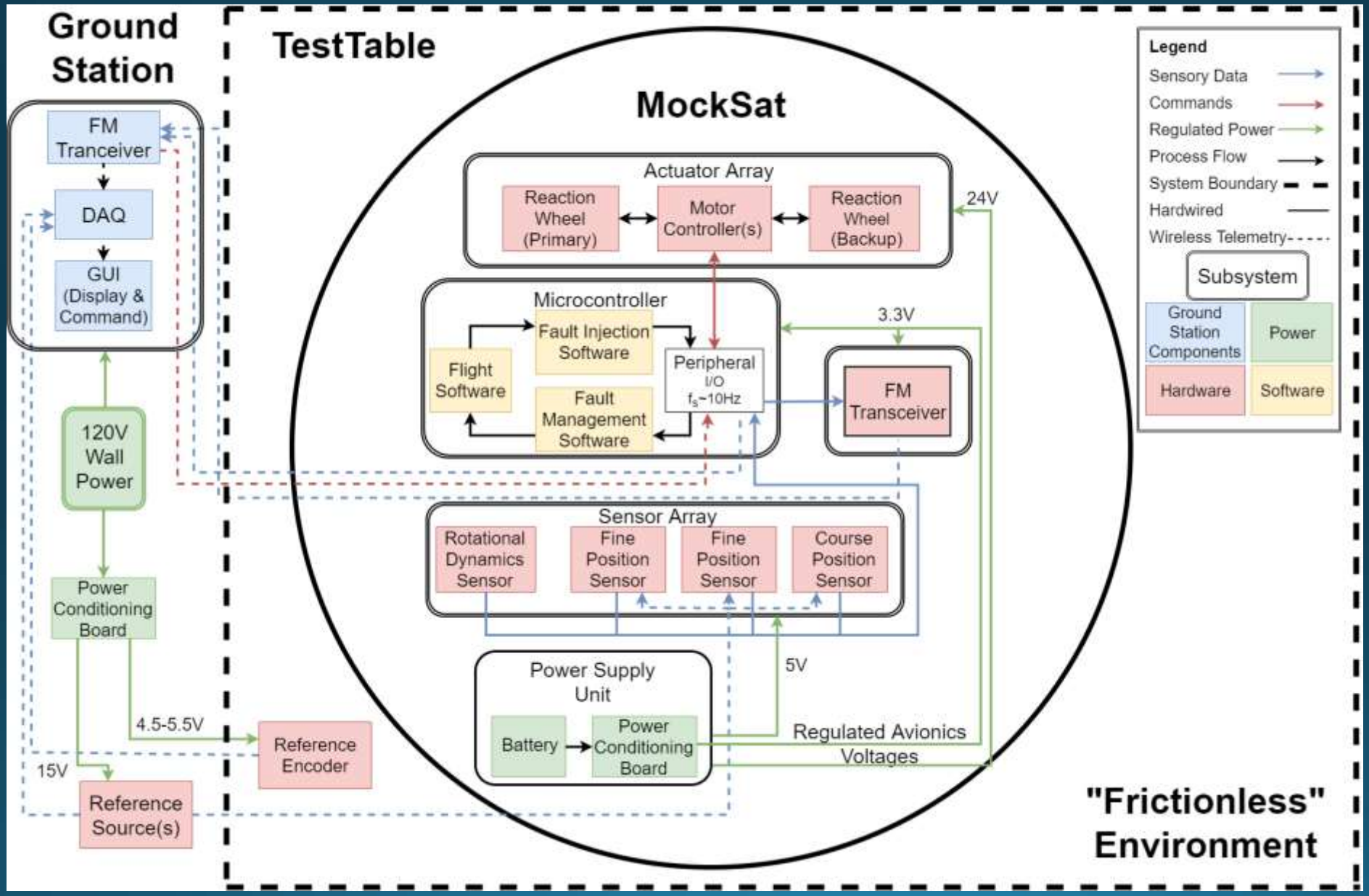

Redefinition of FR 1.3.1 – Low friction surface

FR 1.3.1 – ~~The maximum frictional force between the MockSat and the TestTable during operation shall be no greater than 1% of the maximum frictional force between a block of a representative MockSat material (i.e. aluminum) of a similar mass as the MockSat and a plate of a representative (i.e. polycarbonate).~~

FR 1.3.1 – *The frictional damping constant between the MockSat and the TestTable during nominal operation shall be no greater than* $1.5\ \frac{lbm \cdot in^2}{s}$.

Reasoning:

- Trying to define a surface as "frictionless" is impossible and illogical
- Equally illogical is trying to define the friction in the TestTable as less than some arbitrary value (see old requirement)
- The best way forward is to quantify the friction inherent to our TestTable environment, then write our requirement such that it reflects this.

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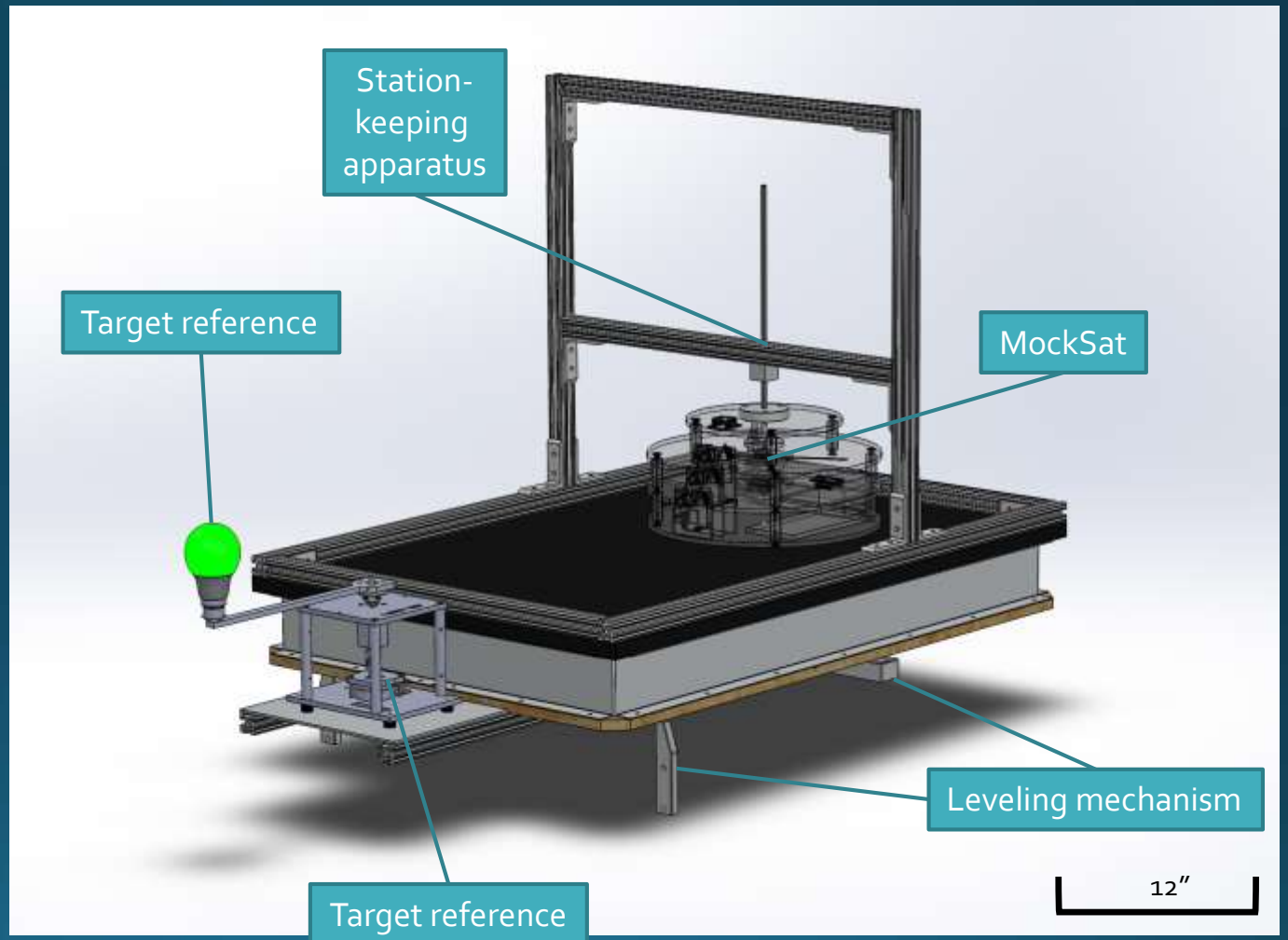
7.0	Q & A	*LLAMAS*

Design Solution – TestTable

The majority of the TestTable is heritage equipment from the *TracSAT* senior project, with the following modifications:

- Half of the TestTable surface has been taped-over in order to increase the lifting capacity of the TestTable (~9lb ⟶ ~24lb).
- A table leveling mechanism has been added.
- Station-keeping is accomplished via a removable bearing-block and rigid shaft apparatus.
- The target reference provides an object for the MockSat to track optically.



Testing suite

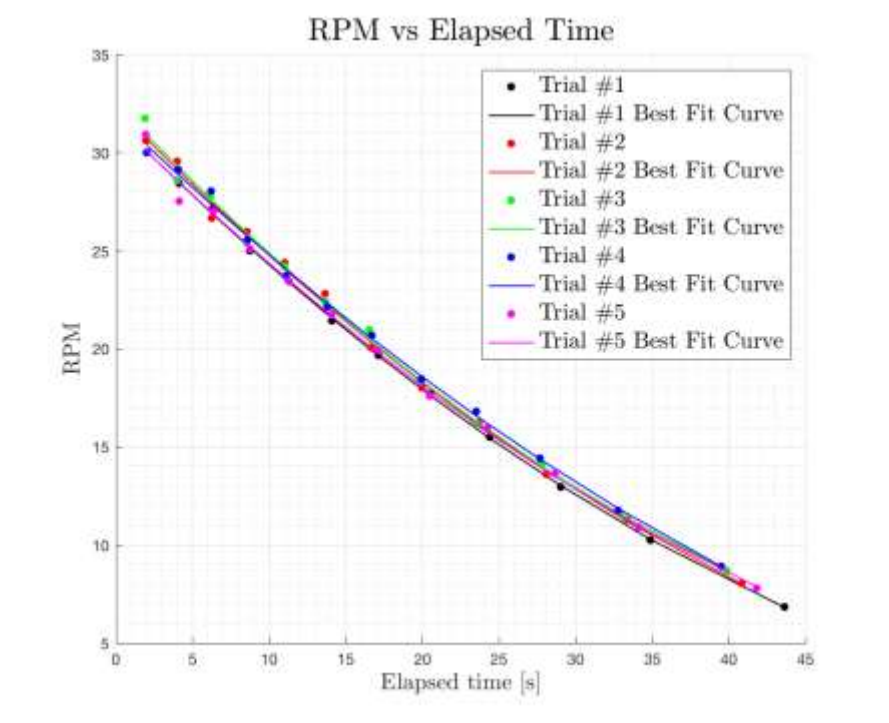
Design Solution – TestTable Losses

Quantification of losses

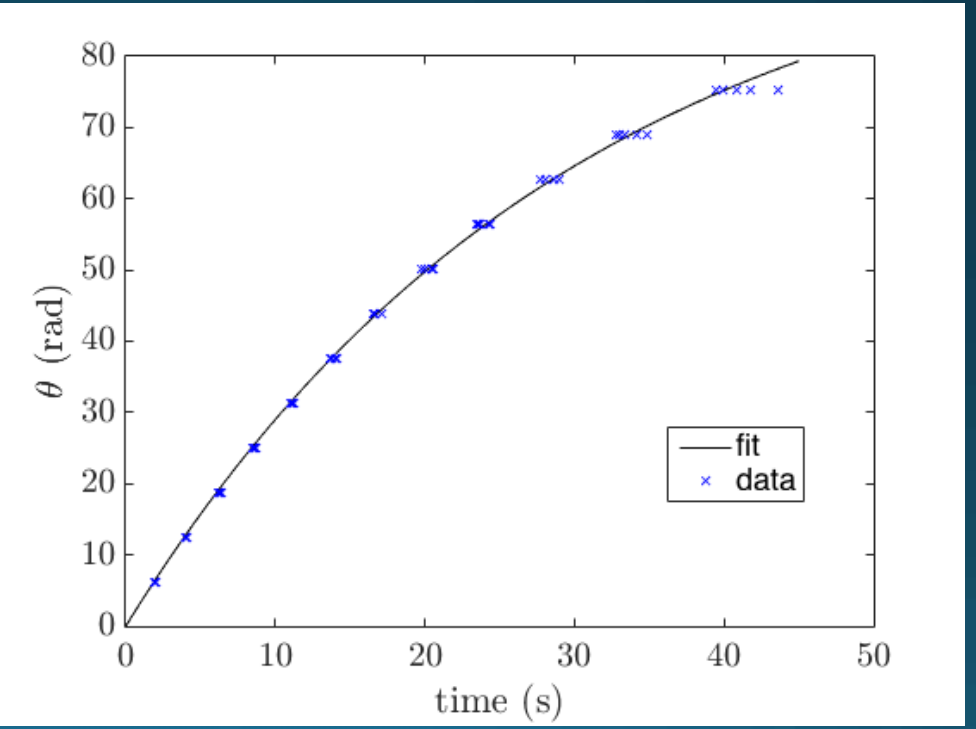
- Key assumption: friction torque varies linearly with angular velocity
- Air friction and bearing block friction measured simultaneously (no need to separate).

$$\tau_{friction} = \left(I_{z,MockSat\ prototype}\right)\left(\frac{d\omega}{dt}\right) = (B_f)(\omega)$$

$$B_f = \frac{I_{z,MS}}{t}\ln\omega = 0.87 \pm 0.05\ \frac{lbm{\cdot}in^2}{s}$$



Tested losses for TestTable



**Error bars hard to see due to scaling, but present.*

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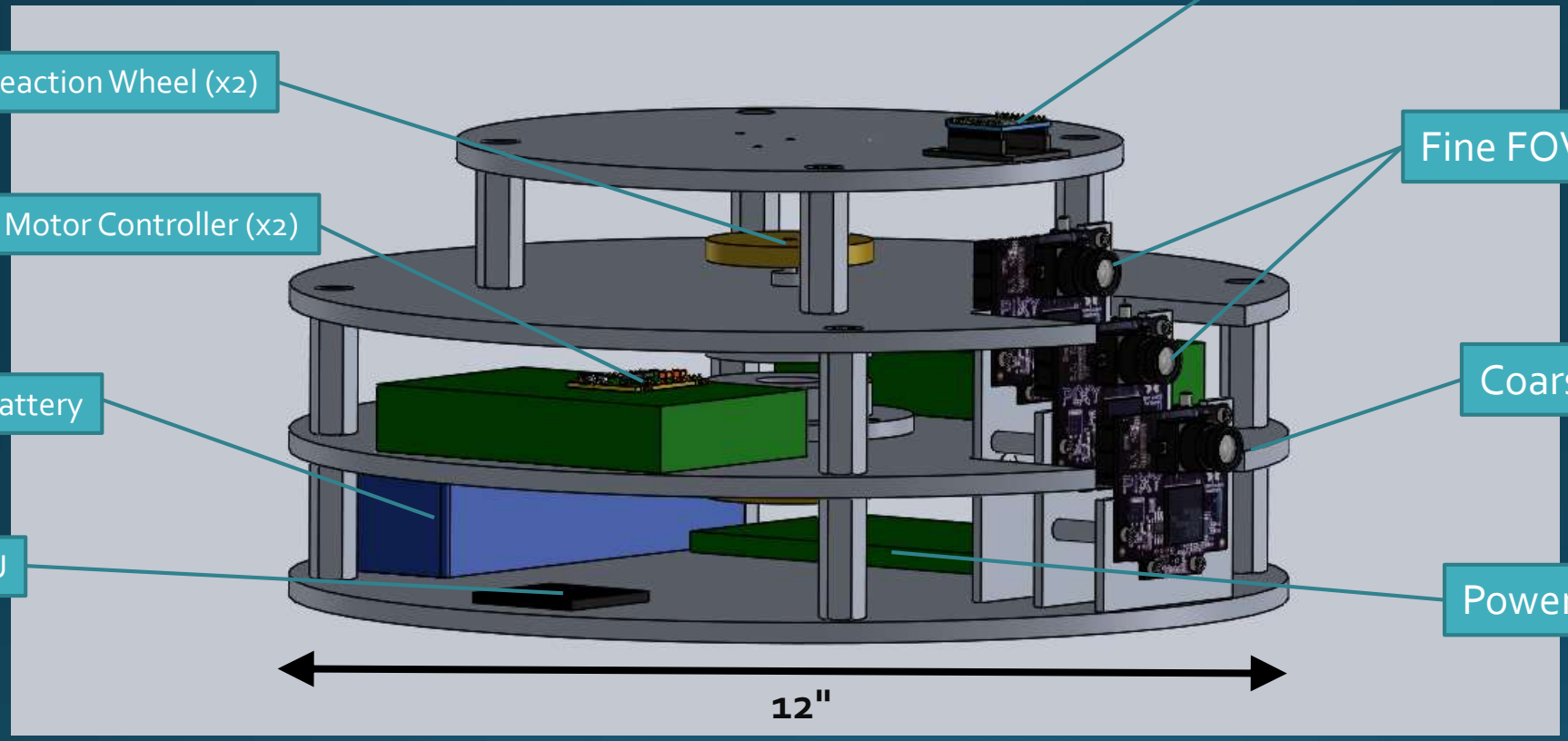
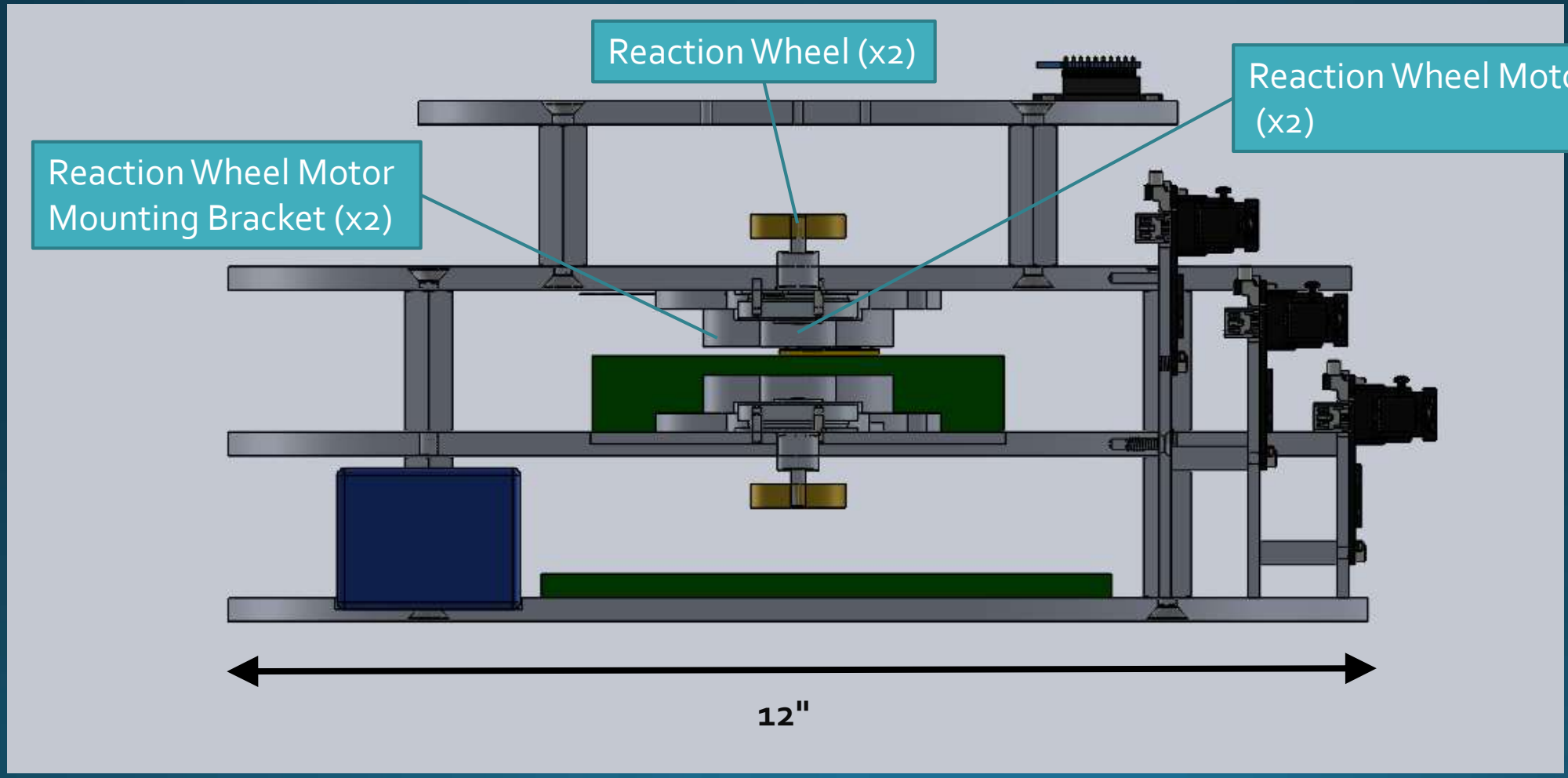
Design Solution – MockSat



MockSat Concept

Total Weight	$14.6\ lbm$
MOI about Axis of Rotation	$240.8\ lbm \cdot in^2$
Height	$5.5\ in$
Width	$12\ in$

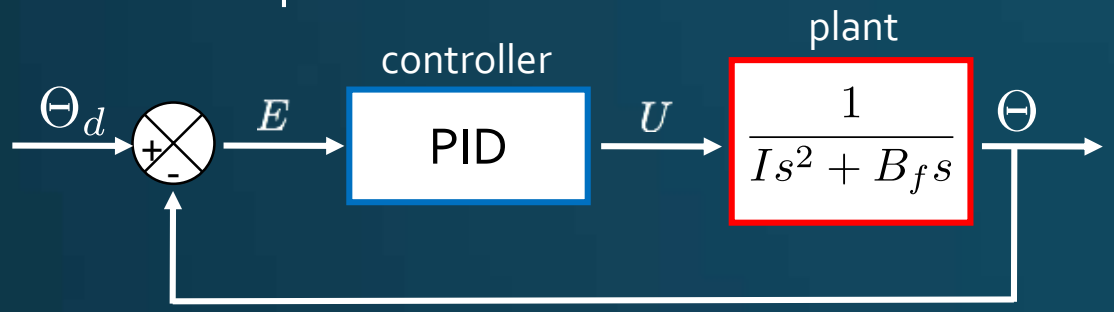
Design Solution – MockSat (Cross-Section)



Cross Section of MockSat Concept

Design Solution – MockSat Controls

Control Loop



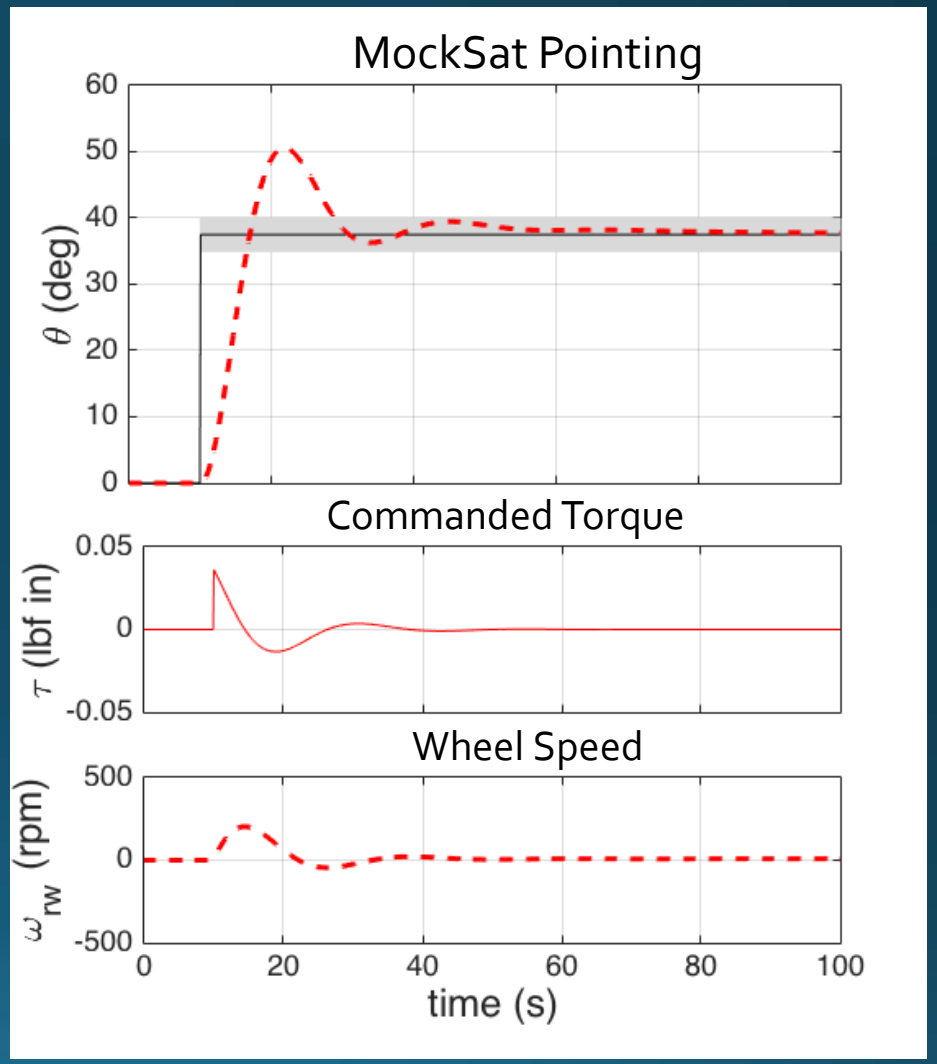
Physical Parameters	
$I_{MS} = 240.5\ lbm \cdot in^2$	MockSat MOI (from SOLIDWORKS)
$I_{RW} = 0.012\ lbm \cdot in^2$	Reaction Wheel MOI (design criteria)
$B_f = 0.8737\ \frac{lbm \cdot in^2}{s}$	TestTable Friction Damping Constant (from experimentation)

Controller Gains

K_p	0.00073358
K_i	$3.62952794 \times 10^{-06}$
K_d	0.02197875
N	0.25132741

PID Controller TF

$$K_p + K_i \frac{1}{s} + K_d \frac{N}{1 + N\frac{1}{s}}$$



Simulated MockSat response to a 37.5° step command

Design Solution – MockSat Motor Selection

- Motor selection
  - Maxon Motors EC6 6mm Brushless 1.5W w/ Hall sensors

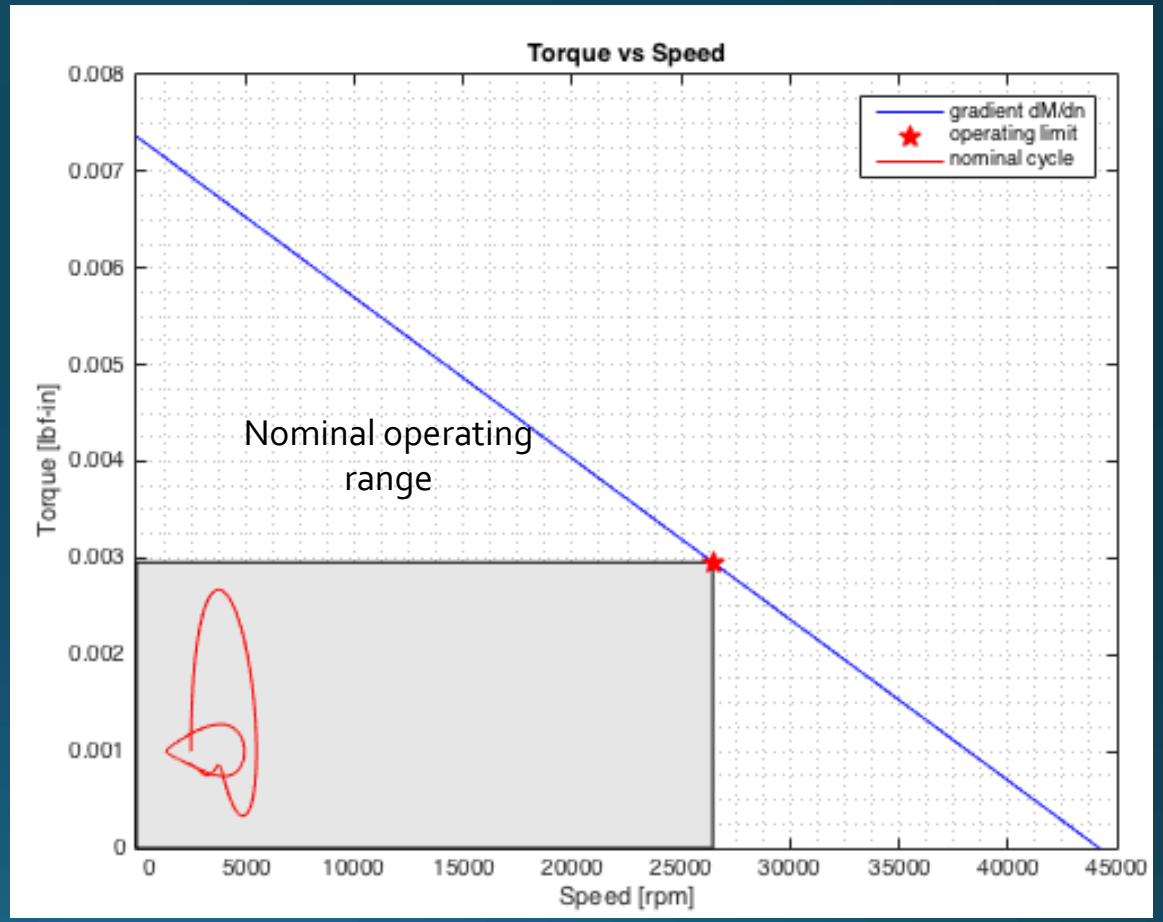
Characteristic	Value
Torque Constant	$0.011 \frac{lbf \cdot in}{A}$
Stall Torque	$0.00061\ lbf \cdot in$
Stall Current	$688\ mA$
Rotor Inertia	$2.392e\text{-}04\ lbm \cdot in^2$

- Reaction wheel moment of inertia can be tailored to improve performance of control system

Required torque

$I \uparrow \quad and \quad \Delta\omega \downarrow$

$I \downarrow \quad and \quad \Delta\omega \uparrow$



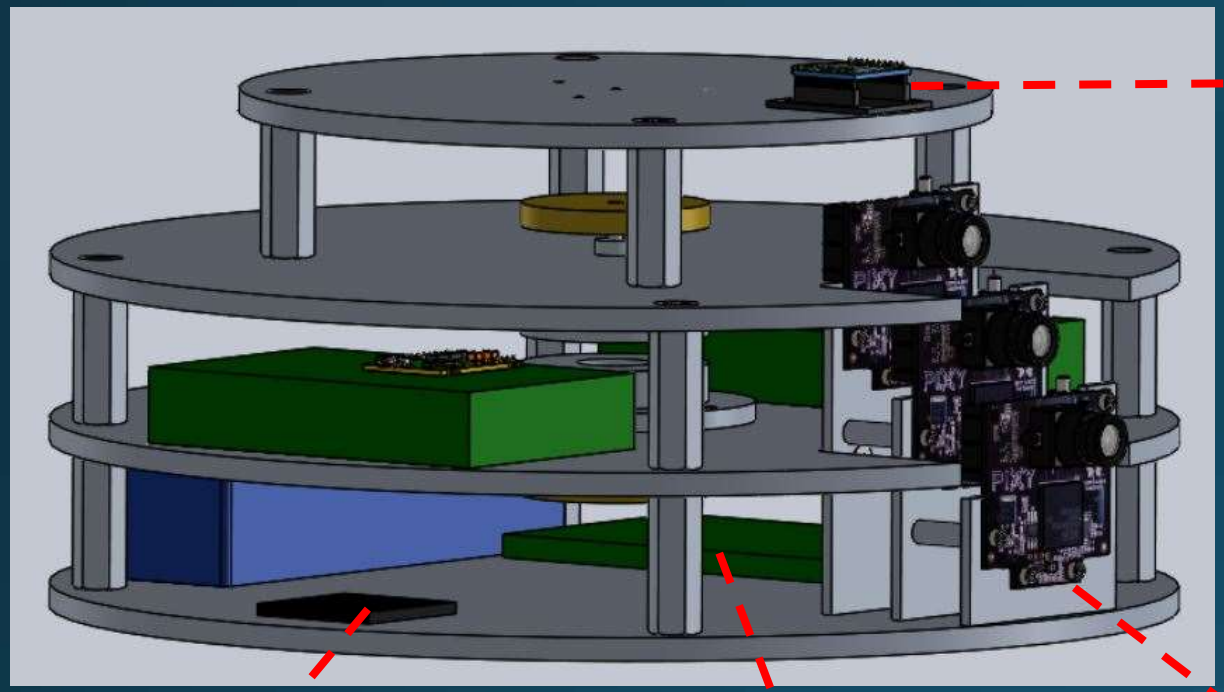
Reaction Wheel Bounds

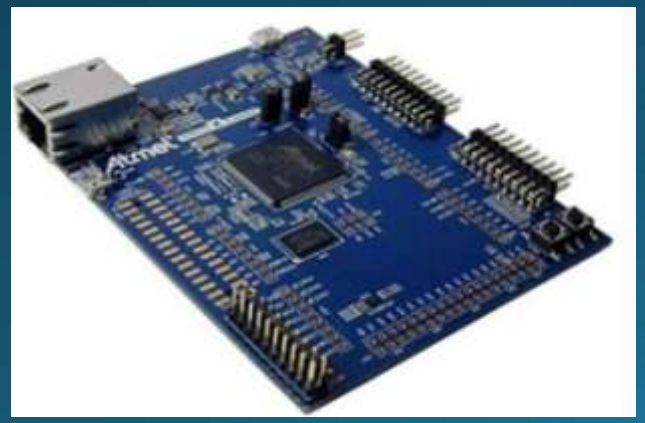
Design Solution – MockSat Motor Controller Selection

- Features of Maxon Motors: ESCON 24/2 Servo Motor Controller
  - Powers motors up to 44W
  - Maximum efficiency of 92%
  - Programmable to motor
  - Compatible with DC and EC motors

Technical Specifications	
Analog Input	12-bit resolution (± 4V)
Digital Input	53.6 kHz PWM (10% to 90% duty cycle)
Operation Mode	Torque (current) control
Torque Resolution ($2.7x10^{-5}$ $lbf \cdot in$ required)	$3.5\ x\ 10^{-6}\ lbf \cdot in$ (CW & CCW)
Feedback	Analog output (± 10V)
Feedback #1	Actual current applied
Feedback #2	Motor shaft speed

Design Solution – Sensors & CDH





- Communications
  - Xbee S2C Zigbee
- Visual Sensors
  - CMUcam5 Pixy
- Microcontroller
  - ATMEL SAME70 XPLD
- Inertial Measurement
  - MPU-6000

Equipment Location in MockSat

Design Solution – Sensors & CDH

- Purpose: To provide necessary sensory data and provide CDH capabilities required for nominal operations

Component	Quantity	Dimensions (inches)	Communication Rate	Data Rate per Cycle	Purpose
Pixy Camera	3	$2.1 \times 2.0 \times 1.4$ (Individual) $3.2 \times 2.5 \times 4.5$ (Suite)	Up to 50 Hz	112 Bits (Individual) 224 Bits (Suite)	Angular Position of MockSat Relative to Reference Target
MPU-6000	1	$.67 \times .67 \times .50$	Up to 400 kHz	16 Bits	Angular Rate of MockSat for Fault Detection Purposes
XBee	1	$.87 \times 1.3 \times .12$	9600 baud	N/A	Ground Station/MockSat Communictions
MicroController	1	$3.3 \times 4.1 \times .63$	Varies	Varies	CDH System

Design Solution – MockSat EPS: Battery Selection

MockSat Power Budget (Using Murata DC-DC Converter)					
Component	Voltage rating (V)	Current Draw (A)	Power Draw (W)	Power Draw From Battery (W)	Efficiency of Voltage Regulation
Motor	12	0.125	1.5	2.91	0.515
Micro-Controller (Atmel SAM E70)	5	0.4	2	2.56	0.780
Xbee Comm System	3.3	0.12	0.396	0.54	0.730
Pixy Camera (3)	5	0.14	0.7	0.90	0.780
MPU 6000 IMU	5	0.25	1.25	1.60	0.780
Total				**10.31**	

If using a 12 V battery, total current draw is 0.86 A

Note:
Efficiency to motor incorporates motor controller efficiency (92%) and motor efficiency (56%)

Incorporating 50% factor of safety and assuming 60% usable range of battery capacity:

$$\frac{0.86\ Ah + 50\%}{60\%} = 2.15\ Ah$$

Turnigy 5 Ah 14.8 V battery to provide margin

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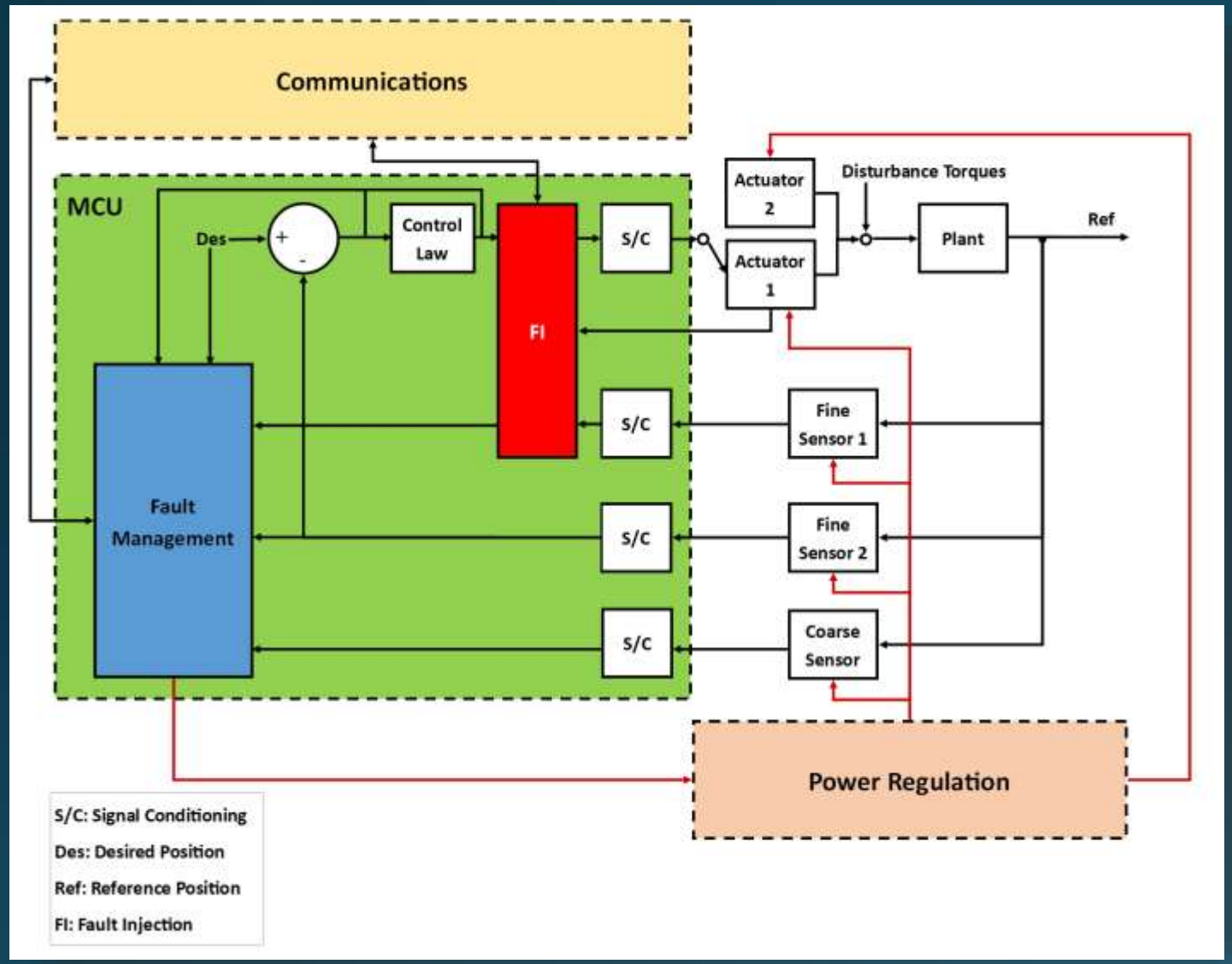
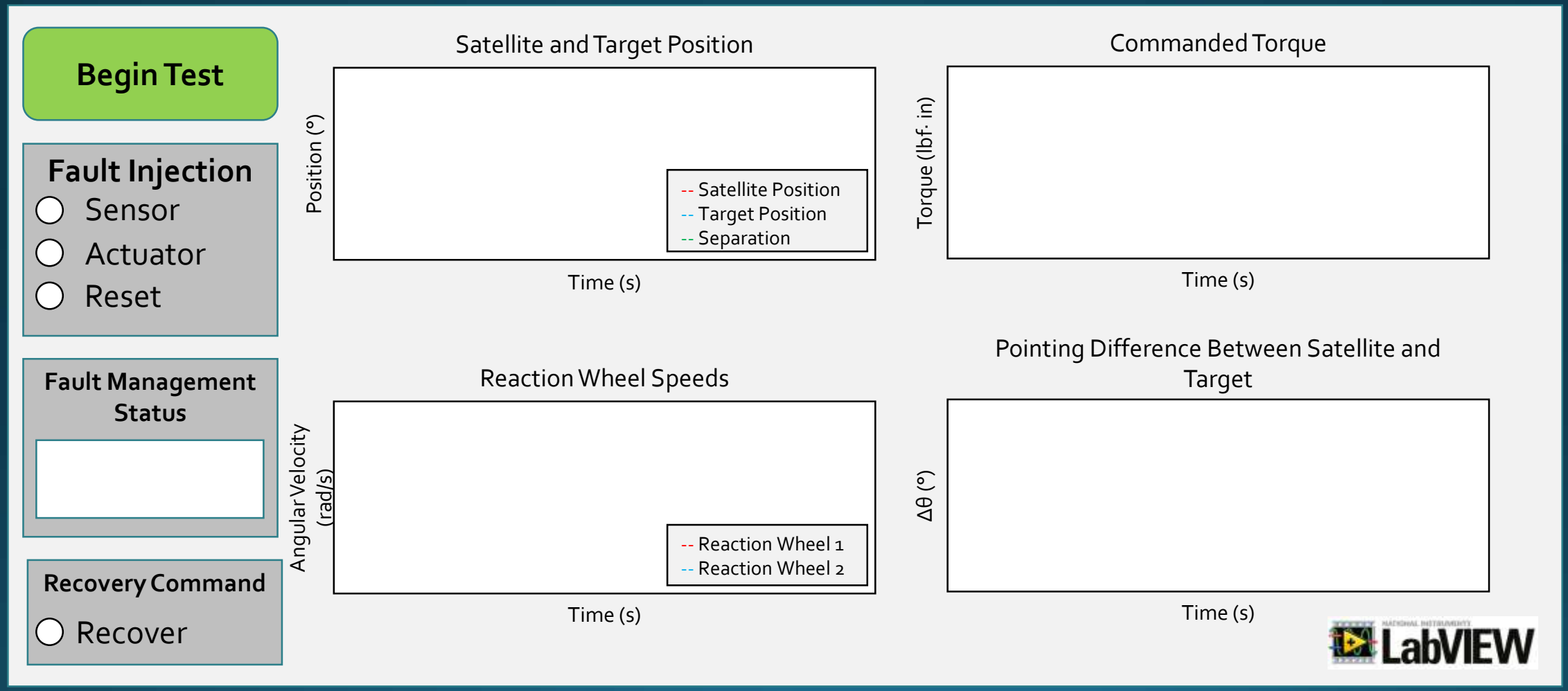
Design Solution – Software: Integration



Interaction between software and hardware

- Software onboard MockSat will:
  - Collect data from ADCS sensors
  - Send commands to control actuators
  - Calculate control torques
  - Communicate with ground station unit (GSU)
  - Inject faults
  - Detect and manage faults
- Onboard software will be written in C++:
  - Team previous experience
  - Commonly used for embedded systems programming

Design Solution – Software: Ground Station Unit (GSU) Graphical User Interface (GUI)



Prototype GUI display

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CPE – Communications & Data Handling

Why CPE?

- The CDH subsystem controls all MockSat functionality.
- Efficient data handling is essential to meeting bandwidth response, pointing, and fault management requirements.
- Implementing multiple communication protocols will be necessary due to limited I/O ports on development board.

CPE – Fault Injection & Fault Management

Why CPE?

- The ultimate goal of this project revolves around demonstrating fault management.
- Fault management is a new and amorphous concept to the team.
- Real faults are multi-symptom and are diagnosed by multiple sensors; we rely on single sensor fault characterization.
  - We are limited by the number of sensors onboard MockSat.
- Software development is high risk because of our inability to predict where potential shortcomings may occur.
  - Due to the inherent difficulty that surrounds fault management

CPE – Pointing Accuracy

Why CPE?

- Demonstrating pointing accuracy is necessary to the success of the project.
- Meeting pointing requirements will involve a complex interaction between sensors, actuators, and control system.
- Verifying pointing accuracy will indicate successful and complete system integration.

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DR&S – Avionics

Functional Requirement 2 – The MockSat shall be equipped with an ADCS that replicates the 0.04 Hz bandwidth response of the GOES-16 satellite to within ± 10°.

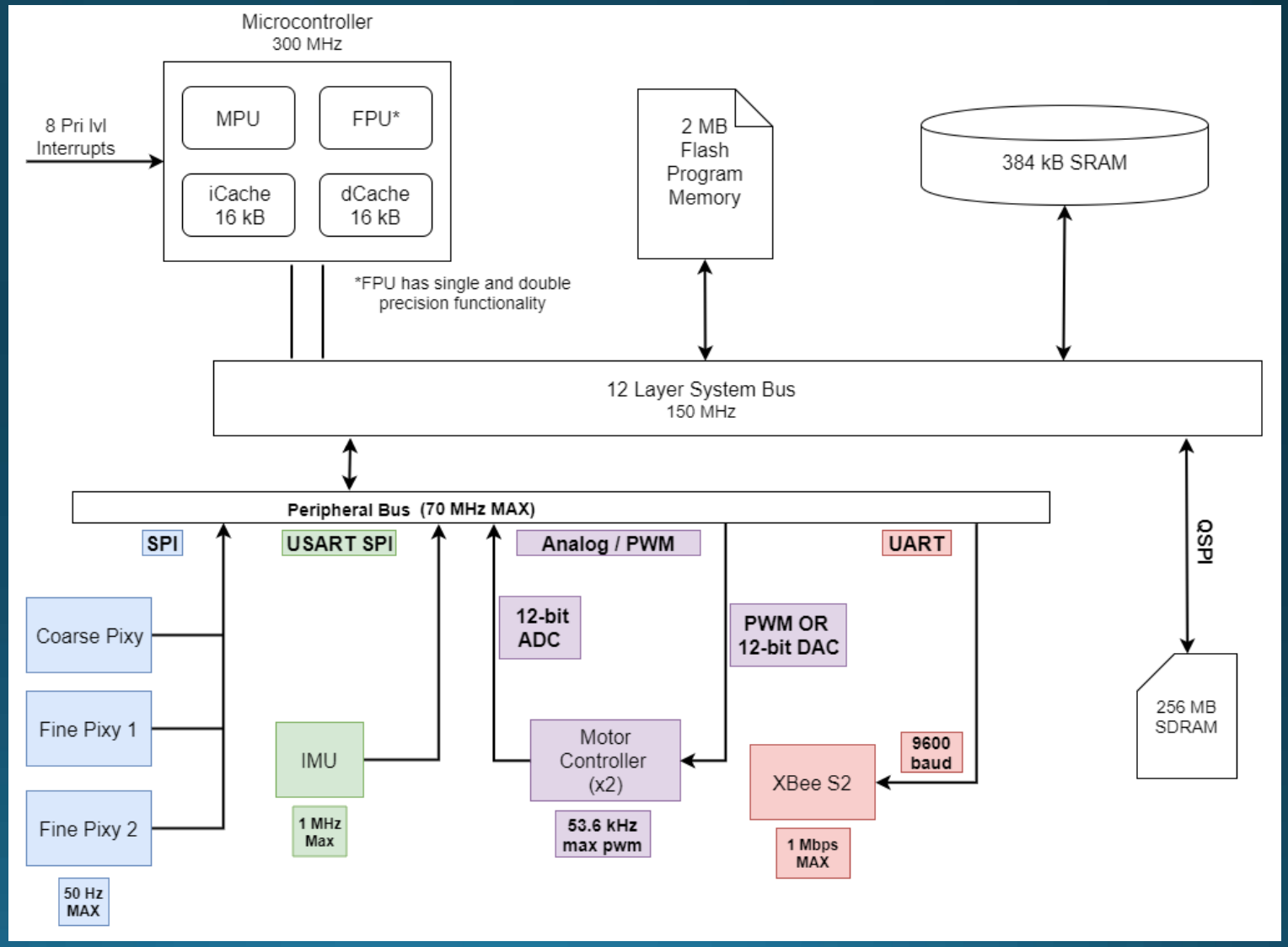
Functional Requirement 3 – The MockSat shall have the ability to maintain a controlled attitude relative to a point of reference within ± 2.5°.

Functional Requirement 5 – The MockSat control software shall recover from a fatal operating fault.

DR&S – Avionics Interface

System:
- Peripheral I/O Clock: 70 MHz
- ADC: 12-bit (0-5V)
- DAC: 12-bit (0-5V)

Components:
1. Pixy camera: SPI (50 Hz)
2. IMU: USART (1 MHz)
3. Xbee S2: UART (115200 max baud)
4. Motor Controller:
   - Input: 12-bit Analog (± 10V)
   - Output: 12-bit (± 4V)
   - Digital I/O: 53.6 kHz PWM
     - 10% - 90% duty cycle



DR&S – Ground Station Unit (GSU) Graphical User Interface (GUI)

Information	Data Transfer Mechanism	Bandwidth
Satellite Position	Wired Encoder	N/A
Target Position	Wired Encoder	N/A
Begin Test	Wireless from GUI	1 bit (1 time)
Fault Injection Initiation	Wireless from GUI	1 bit (1 time)
Recovery Initiation	Wireless from GUI	1 bit (1 time)
Fault Management Status	Wireless from MCU	2 bits (1 time)
Reaction Wheel Speed	Wireless from MCU	1.6 kbps
Redundant Reaction Wheel Speed	Wireless from MCU	1.6 kbps
Mems Gyro Data	Wireless from MCU	1.6 kbps
Commanded Torque	Wireless from MCU	1.6 kbps
$\Delta\theta$	Wireless from MCU	1.6 kbps
Total		**8.4 kbps**

Assume:

- FM status will be sent as bits
- 1 byte for all bits and 1 time data is being transmitted at 50 Hz

Our maximum bandwidth is 8.4 kbps<< 250 kbps

Table 1-01. Specifications of the XBee®/XBee-PRO® RF Modules

Specification	XBee
Performance	
Indoor/Urban Range	Up to 100 ft (30 m)
Outdoor RF line-of-sight Range	Up to 300 ft (90 m)
Transmit Power Output (software selectable)	1mW (0 dBm)
RF Data Rate	250,000 bps
Serial Interface Data Rate (software selectable)	1200 bps - 250 kbps (non-standard baud rates also supported)

Wireless Communication Bandwidth

DR&S – Avionics

Satisfied

Functional Requirement 2 – The MockSat shall be equipped with an ADCS that replicates the 0.04 Hz bandwidth response of the GOES-16 satellite to within ± 10°.

Satisfied

Functional Requirement 3 – The MockSat shall have the ability to maintain a controlled attitude relative to a point of reference within ± 2.5°.

Satisfied

Functional Requirement 5 – The MockSat control software shall recover from a fatal operating fault.

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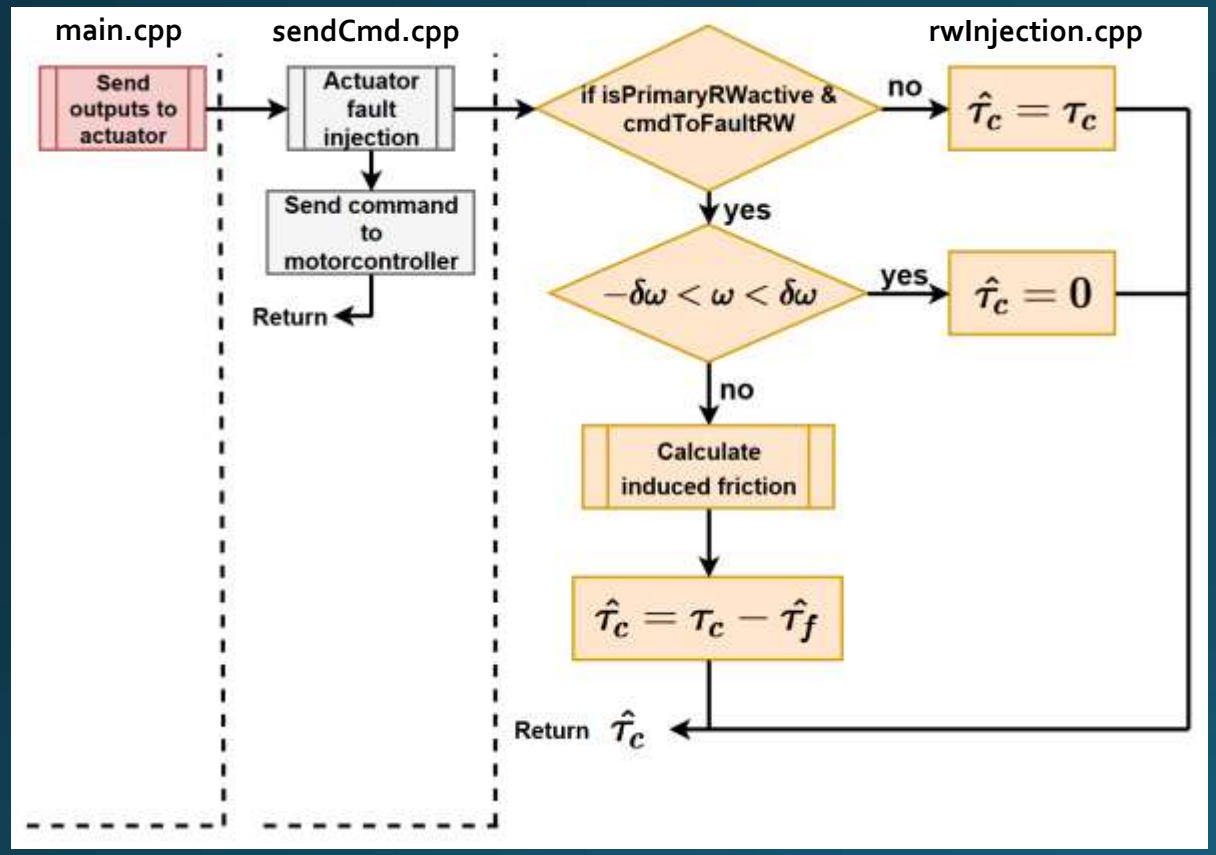
Design Requirements and Satisfaction – Fault Injection and Management

- **FR 4** – The system shall have the ability to introduce a fatal operating fault in either the MockSat's primary reaction wheel or the fine orientation sensor (but not more than one fault at a time).

- **FR 5** – The MockSat flight control software shall recover from a fatal operating fault in either the MockSat's primary reaction wheel or the fine orientation sensor (but not more than one fault at a time) by regaining normal operation.

DR&S – Fault Injection

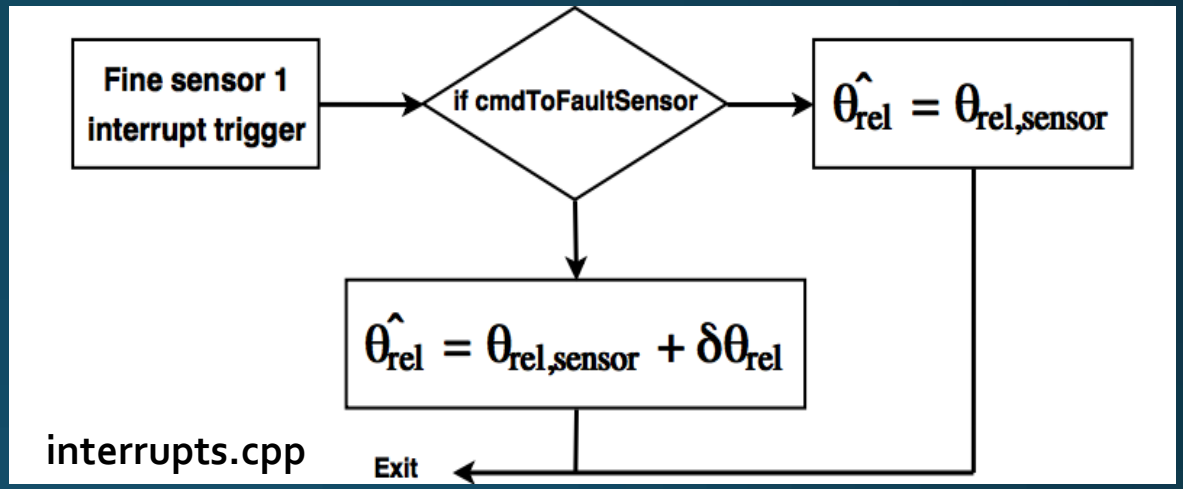
Reaction Wheel Fault Injection



Flowchart for reaction wheel (RW) fault injection

- Reaction wheel fault replicates increased reaction wheel friction by modifying commanded torque
- Increased friction prevents nominal operation, introducing fatal operating fault

Fine Sensor Fault Injection



Flowchart for fine attitude sensor fault injection

- Introduce offset bias in fine sensor data
  - Bias is constant due to interrupt limitations
- This bias causes the satellite to have pointing bias, preventing nominal operation, introducing fatal operating fault

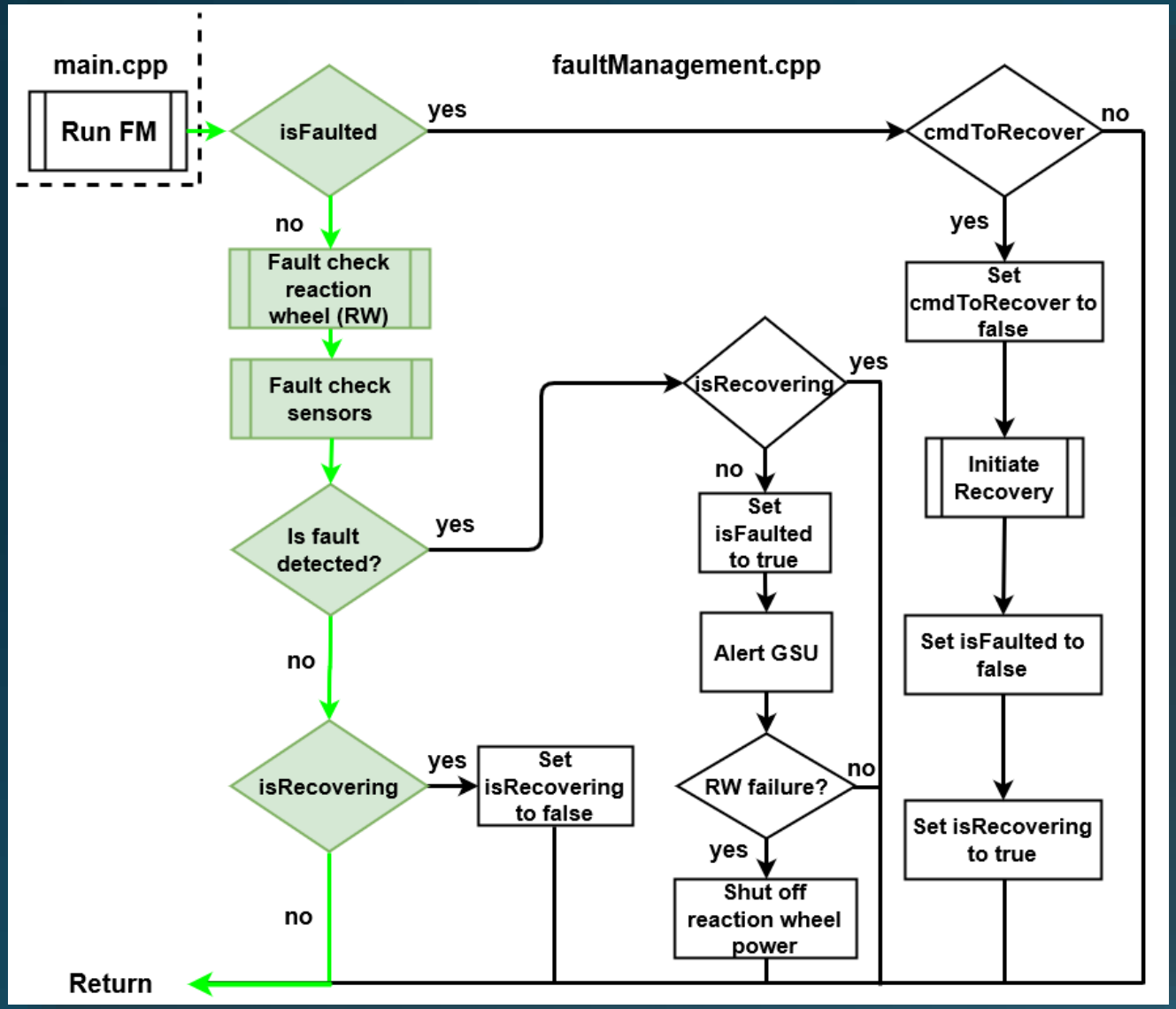
Design Requirements and Satisfaction – Fault Injection and Management

Satisfied

- **FR 4** – The system shall have the ability to introduce a fatal operating fault in either the MockSat's primary reaction wheel or the fine orientation sensor (but not more than one fault at a time).

- **FR 5** – The MockSat flight control software shall recover from a fatal operating fault in either the MockSat's primary reaction wheel or the fine orientation sensor (but not more than one fault at a time) by regaining normal operation.

Design Requirements and Satisfaction – Fault Management

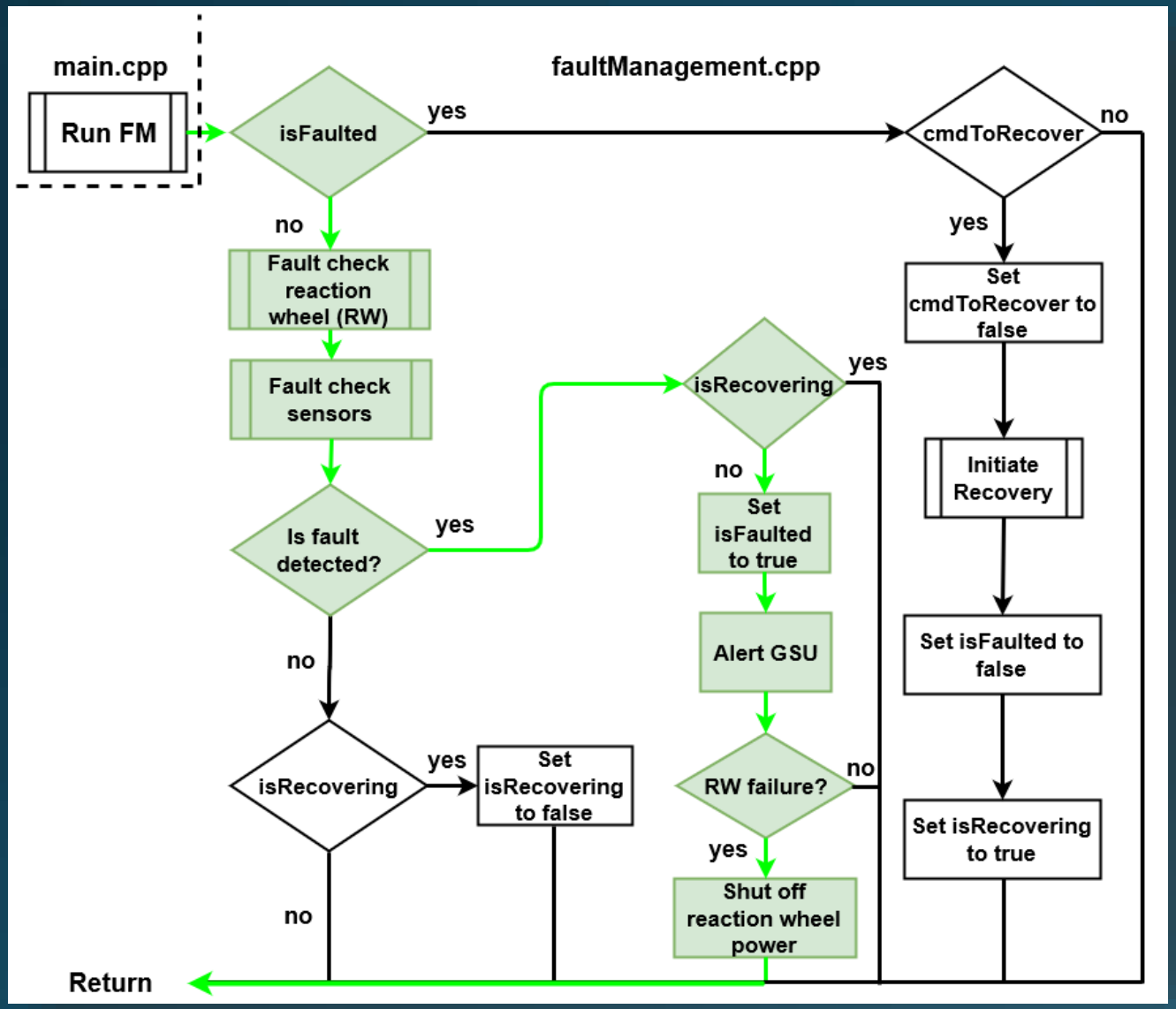


Fault Management Flow Chart: Nominal Operation

Possible MockSat operational states are:

1. Nominal operation
2. Faulted
3. Waiting for Ground Station Unit (GSU)
4. Initiate Recovery Sequence
5. Recovering
6. Recovered

Design Requirements and Satisfaction – Fault Management

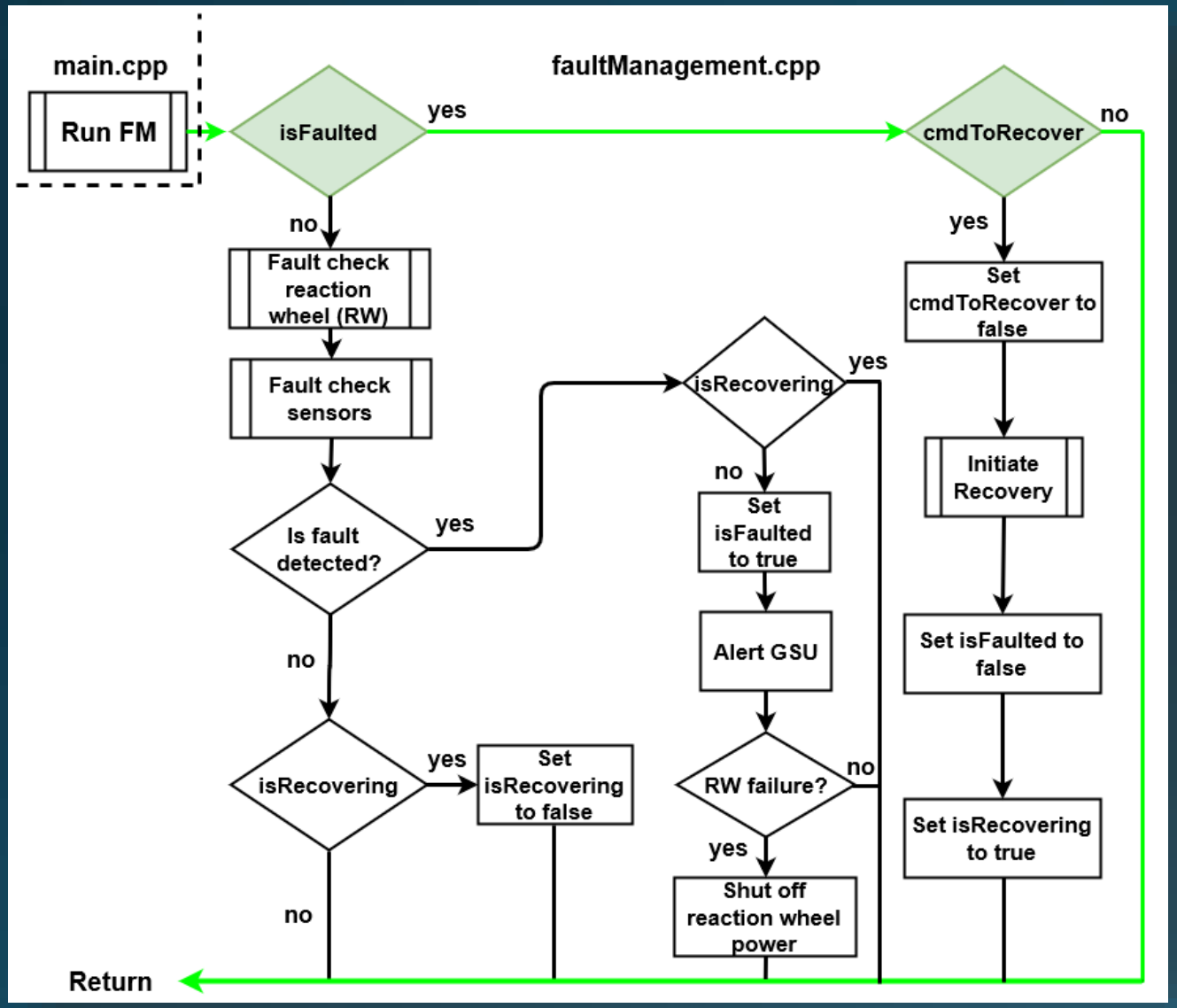


Fault Management Flow Chart: Faulted

Possible MockSat operational states are:

1. Nominal operation
2. Faulted
3. Waiting for Ground Station Unit (GSU)
4. Initiate Recovery Sequence
5. Recovering
6. Recovered

Design Requirements and Satisfaction – Fault Management

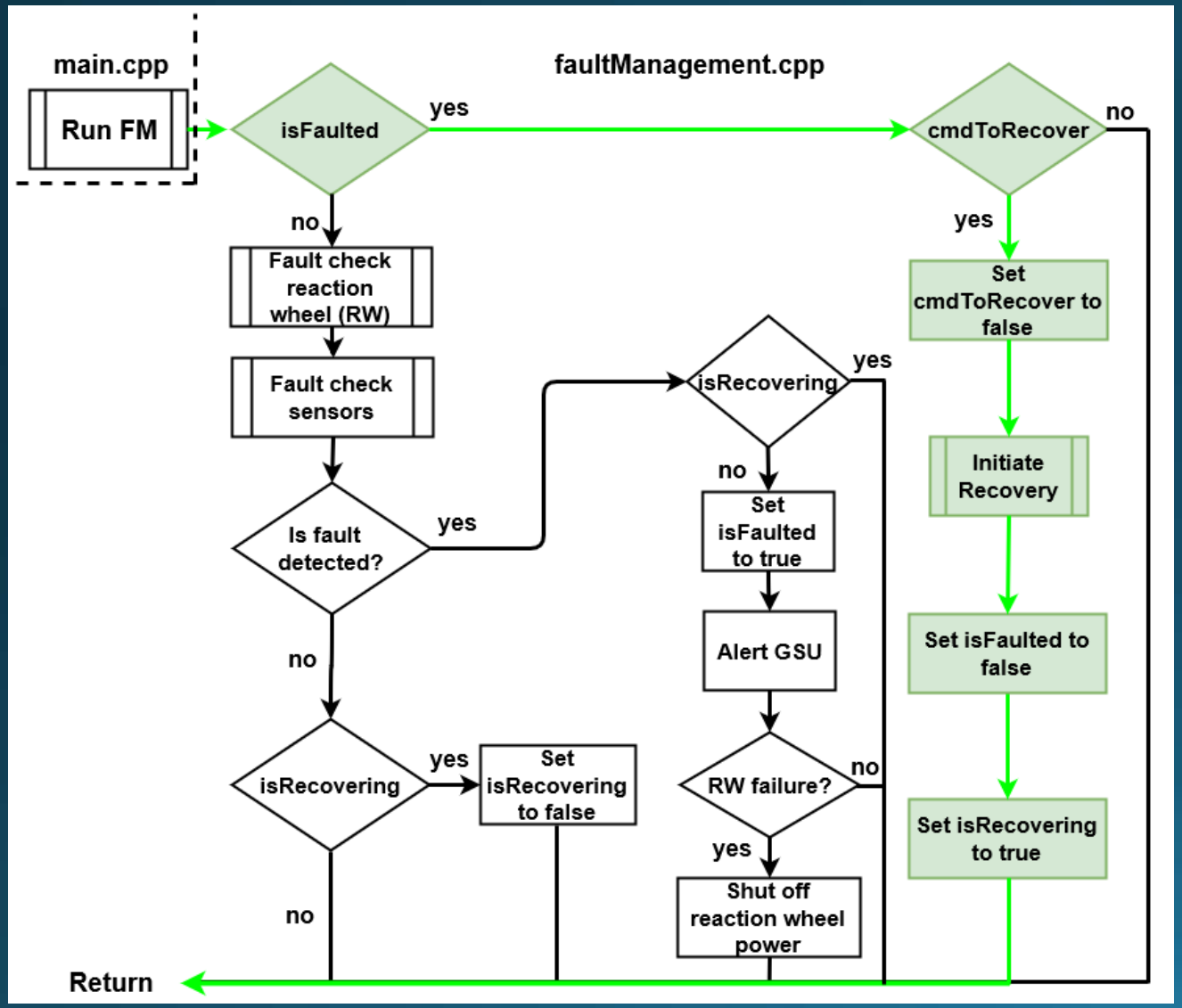


Fault Management Flow Chart: Waiting for Ground Station

Possible MockSat operational states are:

1. Nominal operation
2. Faulted
3. Waiting for Ground Station Unit (GSU)
4. Initiate Recovery Sequence
5. Recovering
6. Recovered

Design Requirements and Satisfaction – Fault Management

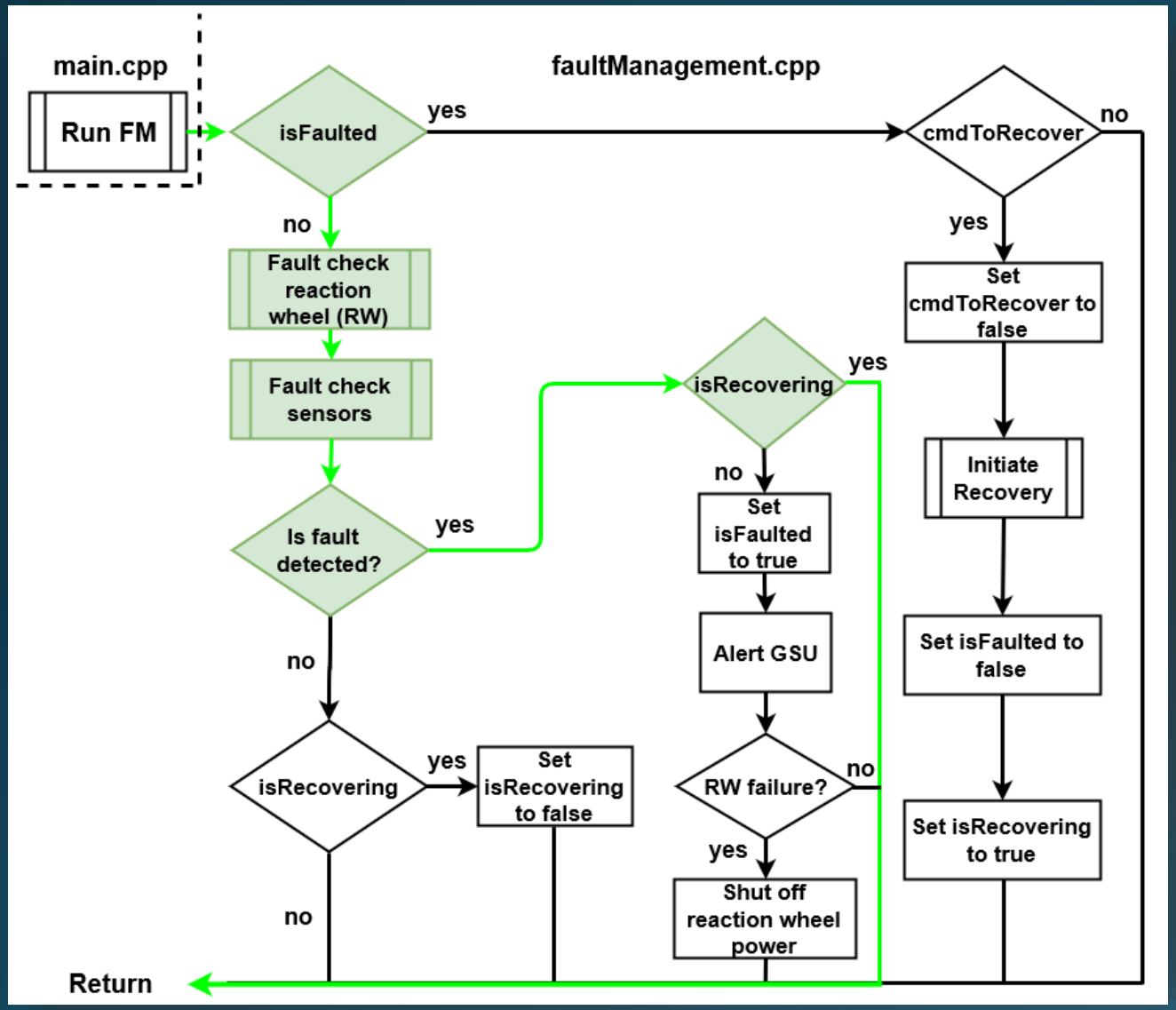


Fault Management Flow Chart: Initiate Recovery Sequence

Possible MockSat operational states are:

1. Nominal operation
2. Faulted
3. Waiting for Ground Station Unit (GSU)
4. Initiate Recovery Sequence
5. Recovering
6. Recovered

Design Requirements and Satisfaction – Fault Management

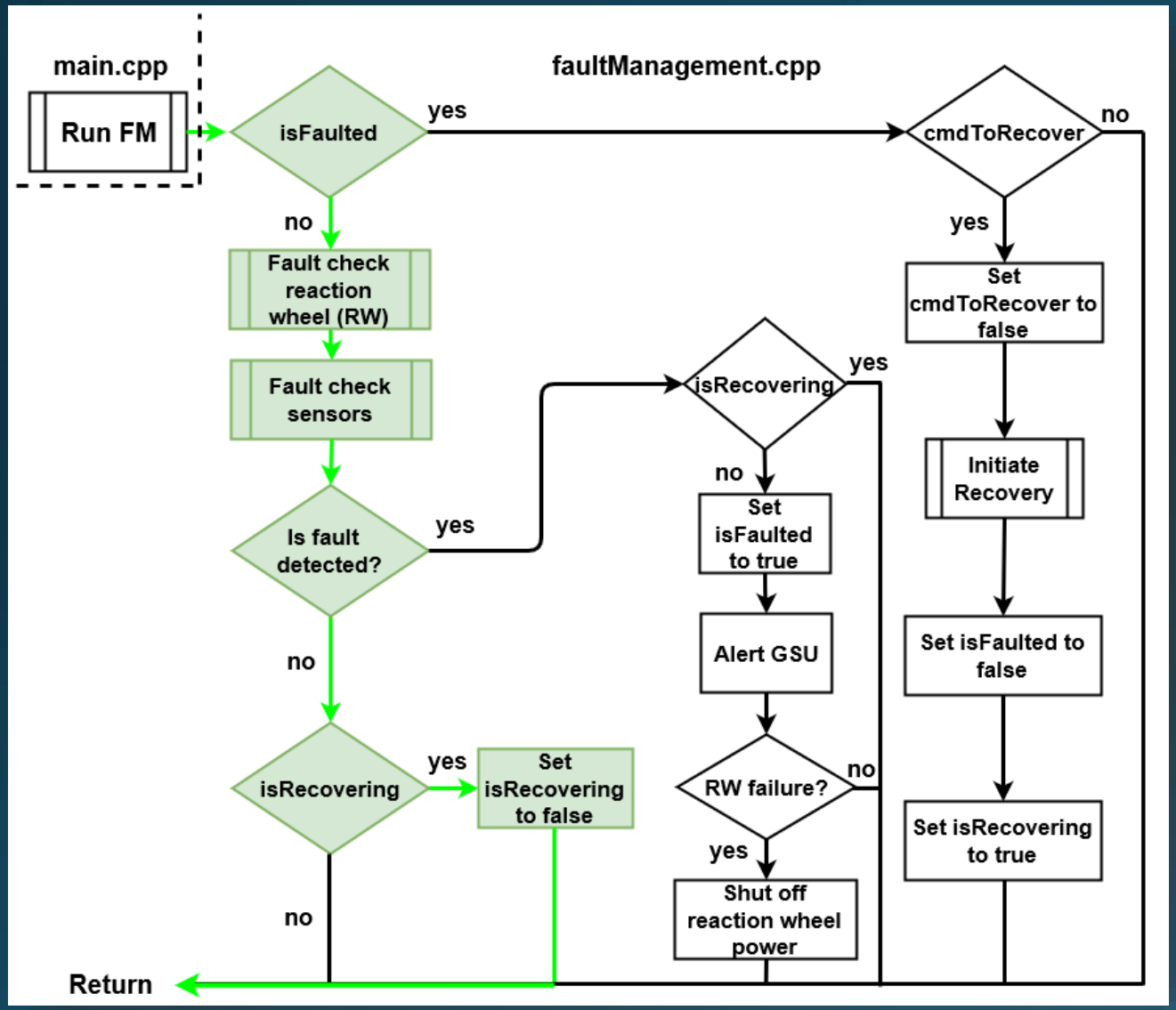


Fault Management Flow Chart: Recovering

Possible MockSat operational states are:

1. Nominal operation
2. Faulted
3. Waiting for Ground Station Unit (GSU)
4. Initiate Recovery Sequence
5. Recovering
6. Recovered

Design Requirements and Satisfaction – Fault Management

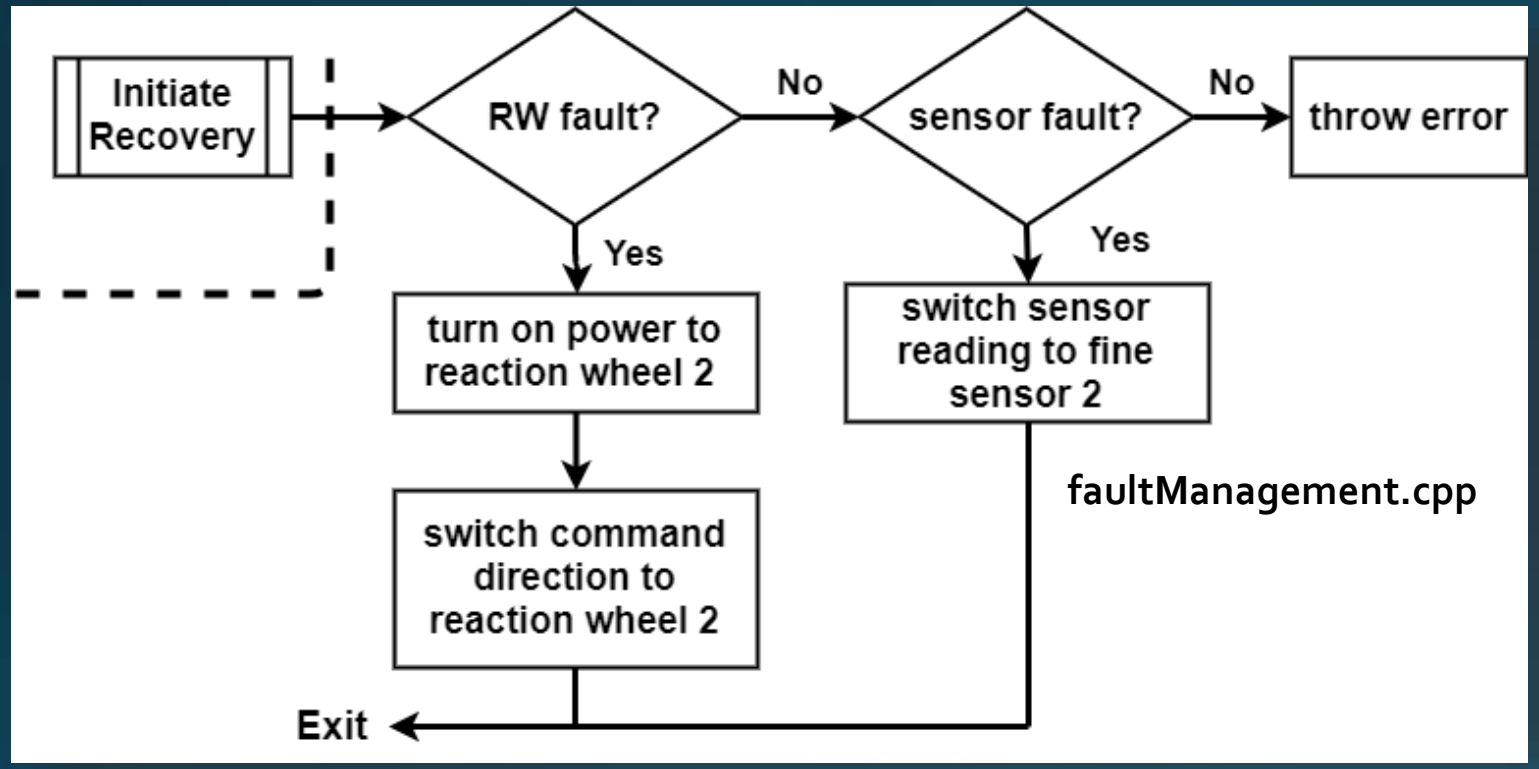


Fault Management Flow Chart: Recovered

Possible MockSat operational states are:

1. Nominal operation
2. Faulted
3. Waiting for Ground Station Unit (GSU)
4. Initiate Recovery Sequence
5. Recovering
6. Recovered

Design Requirements and Satisfaction – Fault Management



Recovery Flowchart

RW Recovery

1. Upon fault detection, shut off power to primary RW
2. Enter a safe mode until primary RW slows to ensure consistent dynamics
3. GSU initiates command to recover
4. Switch power and control to secondary RW

Sensor Recovery

1. Upon fault detection, enter safe mode and wait for GSU command
2. GSU initiates command to recover
3. Switch control to secondary Pixy

Design Requirements and Satisfaction – Fault Injection and Management

Satisfied

- **FR 4** – The system shall have the ability to introduce a fatal operating fault in either the MockSat's primary reaction wheel or the fine orientation sensor (but not more than one fault at a time).

Satisfied

- **FR 5** – The MockSat flight control software shall recover from a fatal operating fault in either the MockSat's primary reaction wheel or the fine orientation sensor (but not more than one fault at a time) by regaining normal operation.

1.0 Project Overview — *Sam O., Dan G.*

2.0 Design Solution

- 2.1 – TestTable — *Dan G.*
- 2.2 – MockSat — *Zack T.*
- 2.3 – Software — *Pol S.*

3.0 Critical Project Elements (CPE) — *Sam O.*

- 3.1 – CDH
- 3.2 – Fault Injection and Management
- 3.3 – Pointing Accuracy

4.0 Design Requirements and their Satisfaction (DR&S)

- 4.1 – Avionics — *Kent L.*
- 4.2 – Fault Injection and Management — *Pol S.*
- 4.3 – Pointing Accuracy — *Ben H.*

5.0 Verification and Validation (V&V) — *Andrew L.*

6.0 Management Items — *Sam O.*

7.0 Q & A — *LLAMAS*

DR&S – Pointing Accuracy (Sensors)

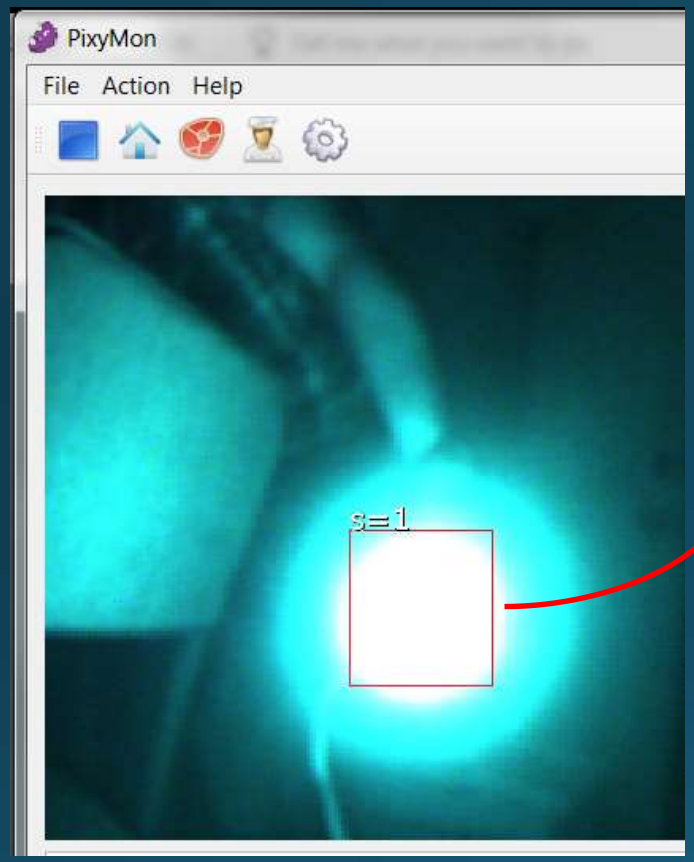
- **Overall Pointing Requirement, FR 3**
- **Coarse Sensor Implementation, DR 3.1.1**
- **Fine Sensor Implementation, DR 3.1.1**

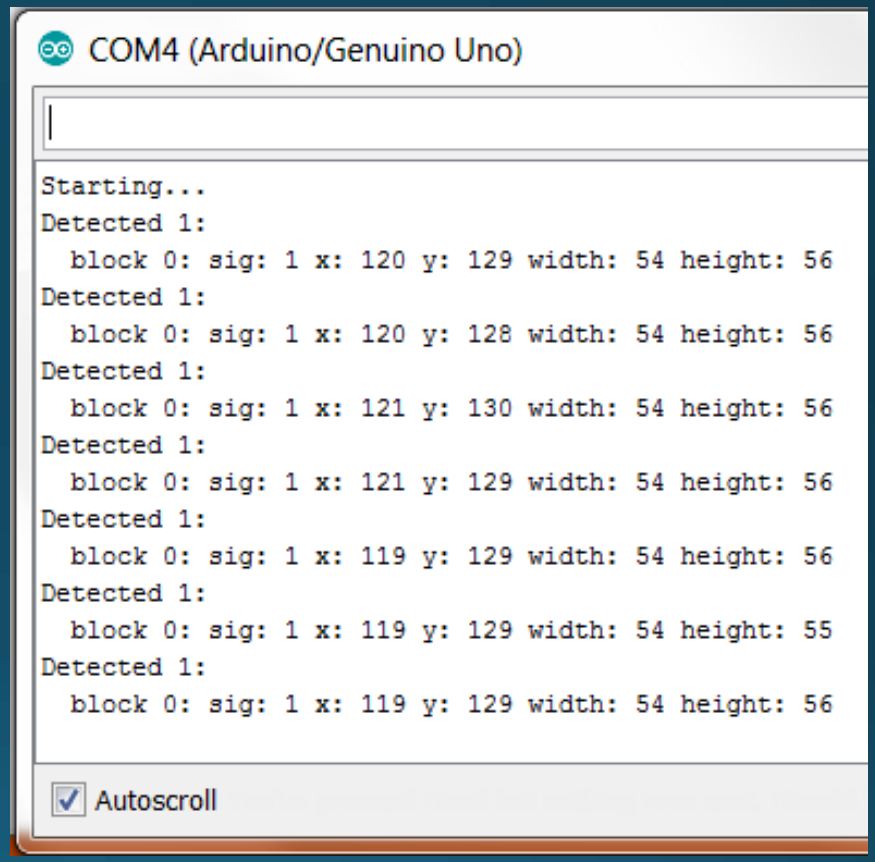
The MockSat shall have the ability to maintain a controlled attitude relative to a point of reference within ± 2.5°.

The MockSat shall have a coarse sensor to provide a wide field of view and get the fine sensor in range.

The MockSat shall have a fine sensor to determine attitude within an accuracy of ± 2.5°.

DR&S – Pointing Accuracy (Sensors)





Pixy functions based upon a hue detection algorithm

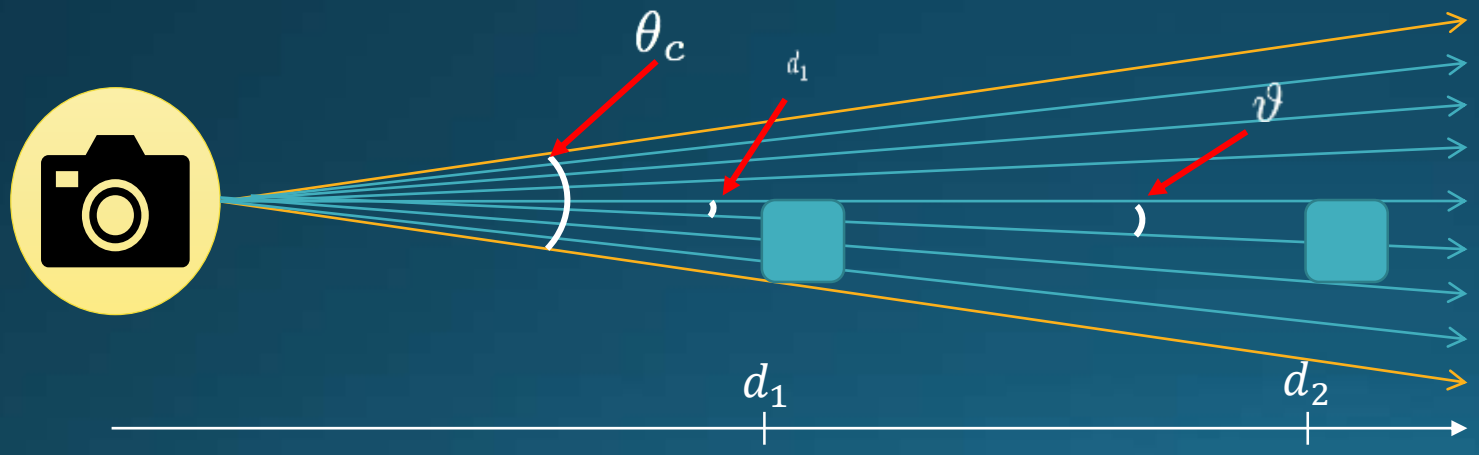
Output information details location and size of the detected object relative to the Pixy's internal coordinate frame

DR&S – Pointing Accuracy (Sensors)

- Pixy output is related to *pixels*, control law needs *angular distance*
  - Need relationship between pixels and angular distance

- Degrees per pixel (ϑ) can be determined by the following equation⟶

$$\vartheta = \arctan\left[\frac{2\tan\left(\frac{\theta_c}{2}\right)}{\Xi}\right]$$



Pixy is capable of utilizing different lenses.

Coarse Sensor

$\theta_c = 75°$

$\vartheta = 0.14\,°/pixel$

Fine Sensor

$\theta_c = 20°$

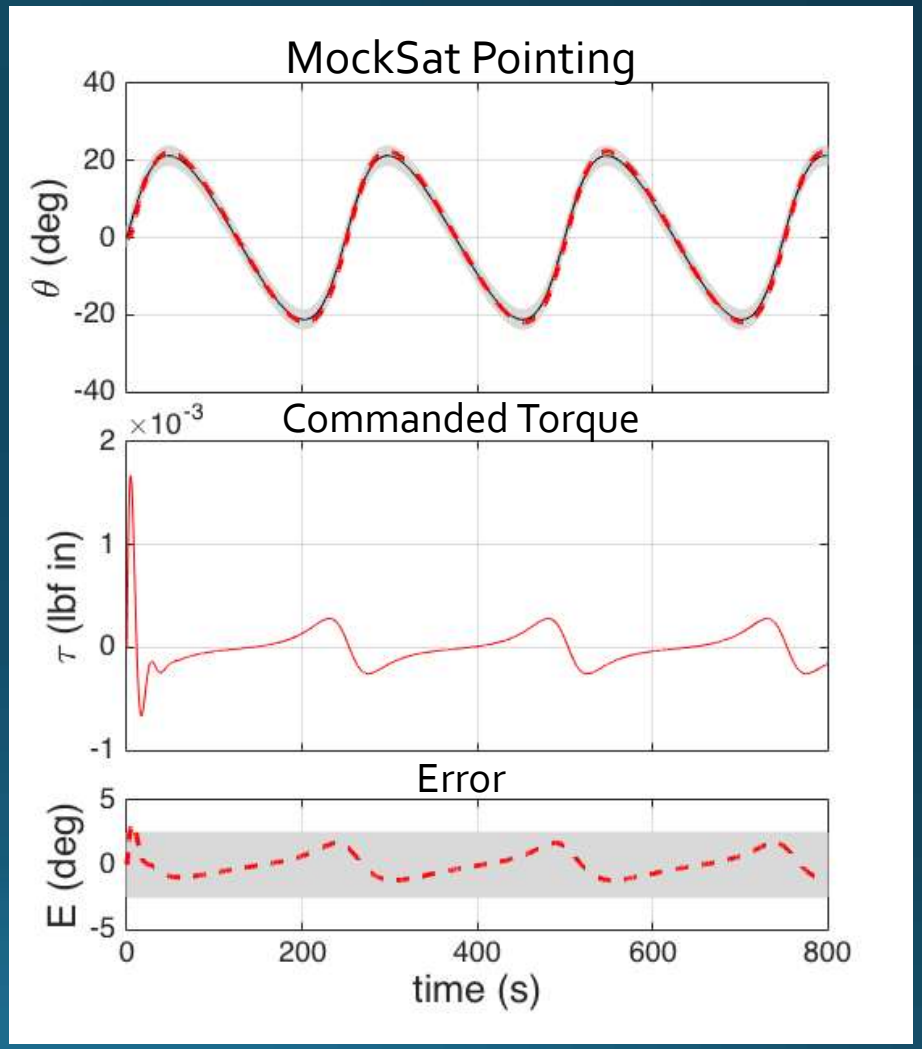
$\vartheta = 0.036\,°/pixel$

Degree per pixel

DR&S – Pointing Accuracy (Controls and Motor)

Controls Model Parameters	
Physical Parameter	**Value**
MockSat Inertia	$240.5\ lbm \cdot in^2$
Friction Damping Constant	$0.87\ \frac{lbm \cdot in^2}{s}$
Target Speed	$0.004\ Hz$
Motor Torque Deadband	$\pm 2.65\ x\ 10^{-5}\ lbf \cdot in$

Motor Parameters (nominal op.)	
Motor	**MockSat**
$\tau_{nom,MIN}$ $\tau_{nom,MAX}$	$2.65 \times 10^{-5}\ lbf \cdot in$ $28.02 \times 10^{-5}\ lbf \cdot in$
$I_{nom,MIN}$ $I_{nom,MAX}$	$3.60\ mA$ $38.3\ mA$
$Motor\ \tau\ deadband$: $\pm 2.65 \times 10^{-5}\ lbf \cdot in$	



Nominal Pointing

DR&S – Pointing Accuracy (Sensors)

Satisfied

• **Overall Pointing Requirement, FR 3**	The MockSat shall have the ability to maintain a controlled attitude relative to a point of reference within ± 2.5°.

Satisfied

• **Coarse Sensor Implementation, DR 3.1.1**	The MockSat shall have a coarse sensor to provide a wide field of view and get the fine sensor in range.

Satisfied

• **Fine Sensor Implementation, DR 3.1.1**	The MockSat shall have a fine sensor to determine attitude within an accuracy of ±2.5°.

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2.0	Design Solution	
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5.0	Verification and Validation (V&V)	*Andrew L.*
6.0	Management Items	*Sam O.*
7.0	Q & A	*LLAMAS*

Verification and Validation – Pointing Accuracy

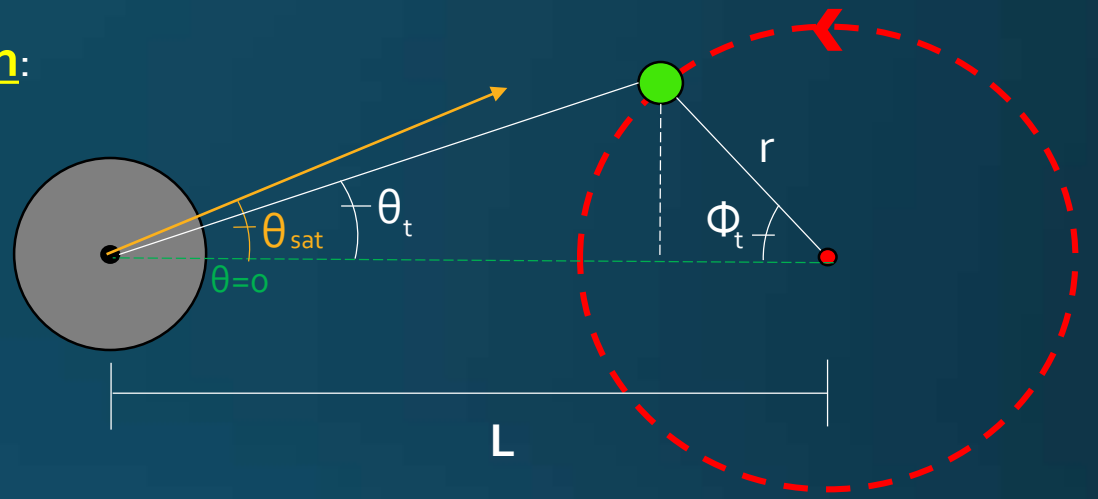
Purpose: Determine pointing accuracy of the MockSat

Requirements Validated:
- Determine attitude within an accuracy of ± 2.5°

Location: Lockheed Martin Projects Room

Method: Compare data from encoder on MockSat to derived data of encoder on reference target actuator.

Breakdown:



One encoder located on the rotating center of MockSat (•) and the other on the reference target actuator (•)

$$\theta_t = tan^{-1}\left(\frac{r * sin\Phi_t}{L - (r * cos\Phi_t)}\right)$$

$\theta_t = \theta_{sat} \pm 2.5^0$ for nominal operation

Verification and Validation – Bandwidth Response

Purpose: Determine bandwidth response of the MockSat

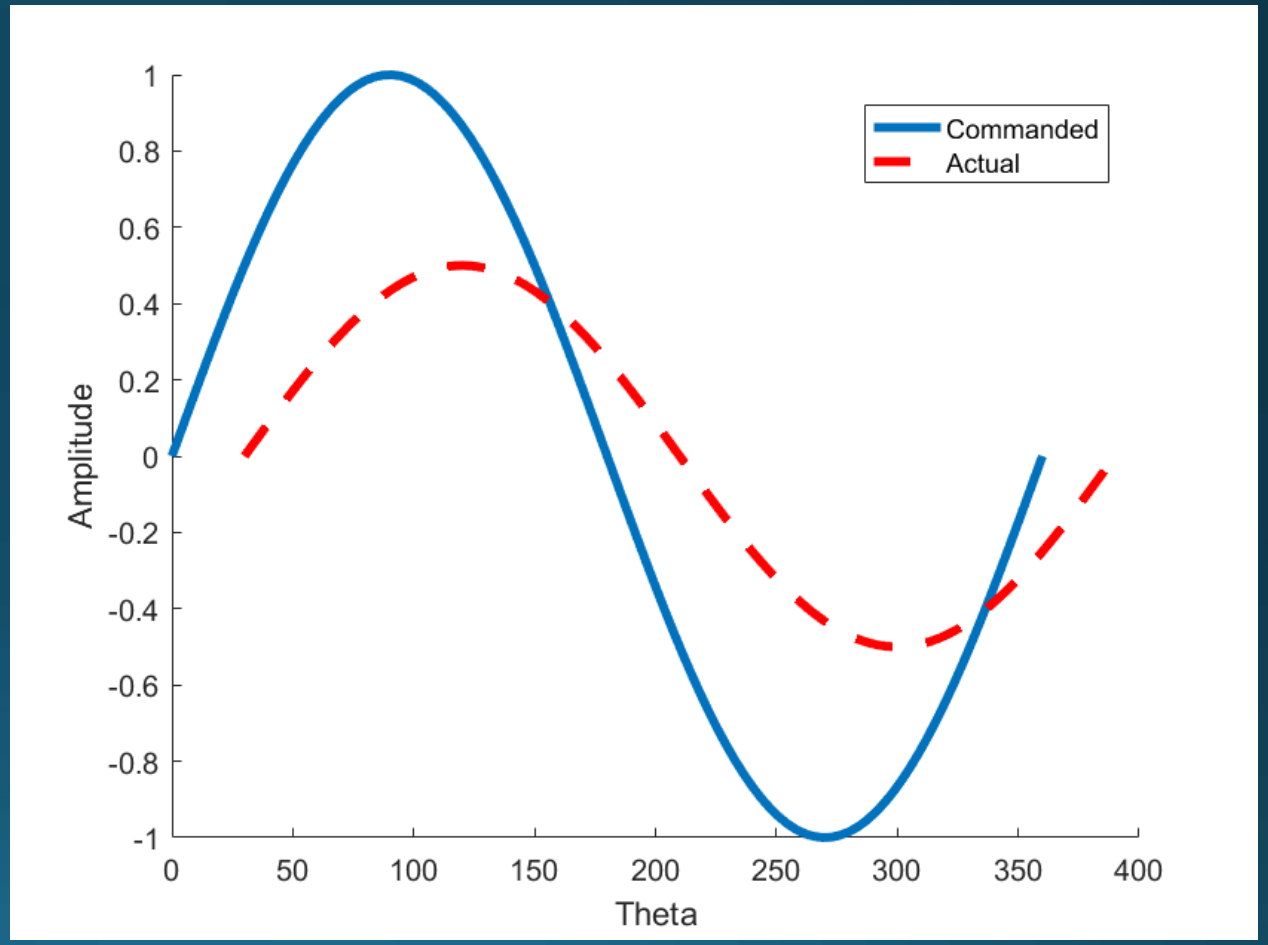
Requirements Validated:

- Replicates the 0.04 Hz bandwidth within ± 10%

Location: Lockheed Martin Projects Room

Method: Replace Pixy controls with a direct 0.04 Hz sinusoidal input and verify motion against predicted model.

Breakdown:



Expected behavior of the MockSat is a sinusoid with half of the amplitude of the commanded input with some phase offset.

Verification and Validation – Fault Injection

Purpose: To inject fault in the system

Requirements Validated:
- System shall have the ability to introduce a single fatal operating fault

Location: Lockheed Martin Projects Room

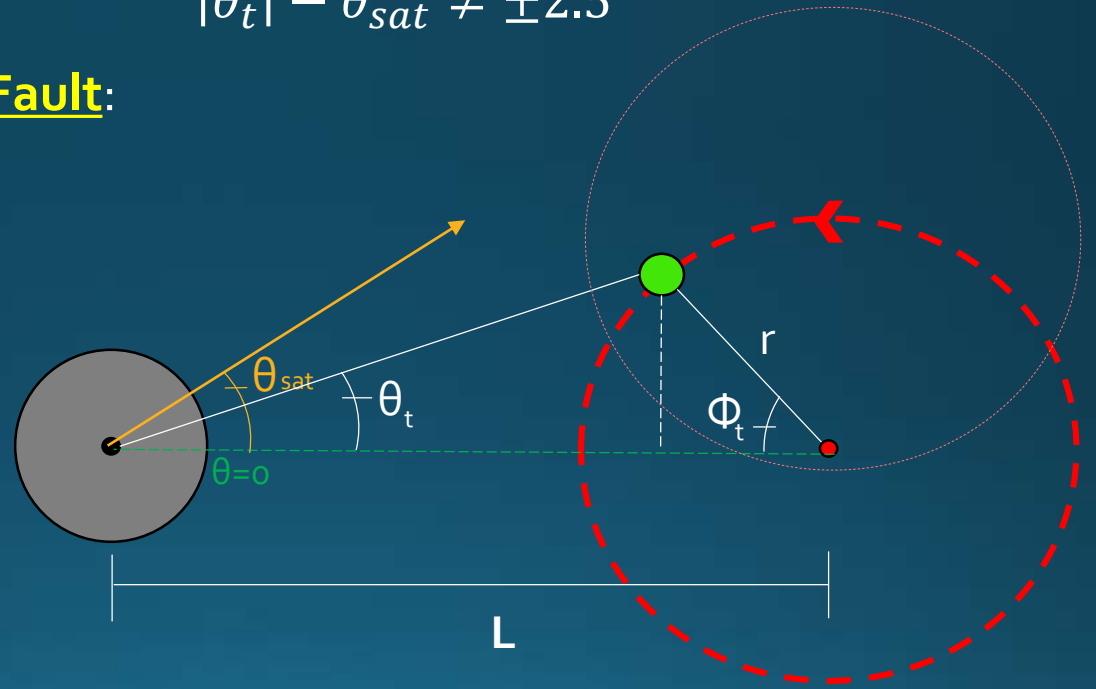
Method: Analyze MockSat encoder data

Breakdown:
- Reaction Wheel Fault: Simulate increase friction by modifying commanded torques
- Pixy Fault: Skewing actual location of target from given Pixy data

Reaction Wheel Fault:
- Sluggish behavior from MockSat, not able to catch up to target position

$$|\theta_t| - \theta_{sat} \neq \pm 2.5°$$

Pixy Fault:



$$\theta_{sat} \pm 2.5° \neq \theta_t$$

(actual motion of MockSat movement recorded by encoders can not be speculated at this time pending control law and coarse and fine sensor interaction)

Verification and Validation – Fault Management

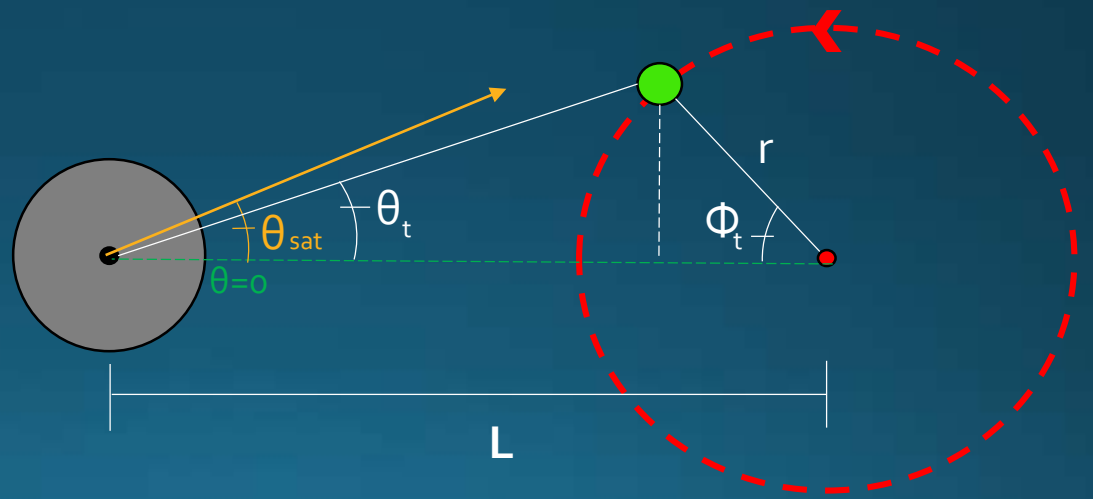
Purpose: Manage fault by redundant components

Requirements Validated:
- Software shall recover from a fatal operating fault

Location: Lockheed Martin Projects Room

Method: User interface from control station

Breakdown:
- Will not meet pointing requirements and alert user
- User will switch from primary to secondary system
- MockSat will go into a recovery procedure to relocate target and begin tracking nominally



$$\theta_t = \theta_{sat} \pm 2.5^0$$

V&V – Ground Station Unit (GSU) Graphical User Interface (GUI)

The GSU GUI needs to:

- *Provide a readout of:*
  - *Absolute pointing position of satellite*
  - *Absolute angular position of target*
  - *Relative position of satellite pointing to target for verification (calculated by external encoders)*
  - *Reaction wheel speed (primary and secondary)*
  - *Relative position of satellite pointing to target (calculated by the satellite ADCS)*
  - *Fault Management status (whether system is faulted, and type of fault)*
- *Provide user control for:*
  - *Triggering fault injection*
  - *Initiate recovery after fault detection*

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7.0	Q & A	*LLAMAS*

Risk Assessment

	Risk Matrix					
Likelihood	Very Likely					
	Likely				1	2
	Possible				3	
	Unlikely					
	Very Unlikely					
	Acceptable	Negligible	Minor	Moderate	Significant	Severe
	Marginal					
	Unacceptable	Severity				

1. Lack of torque resolution
2. Fault Management Implementation
3. ADCS Integration

Risk Assessment – Mitigation

Risk: Lack of torque resolution		
Cause: Motors do not have adequate torque resolution	**Effect:** Unable to provide commanded torque to meet pointing requirements	
Risk Mitigation		
Action: Proper motor selection, accurate torque characterization	**Success Criteria:** Pointing requirements satisfied	**Old Risk Level:** High
		New Risk Level: Marginal
		Risk Mode: Technological

Risk Assessment – Mitigation

Risk: Fault Management Implementation		
Cause: Tailoring a consistent specific response to a generalized suite of hardware	**Effect:** Fault management system does not work on different sensors and actuators	
Risk Mitigation		
Action: Create a fault management architecture that attempts to solve the modularity aspect	**Success Criteria:** End up with a fault management architecture that is applicable to other projects	**Old Risk Level:** High **New Risk Level:** Marginal **Risk Mode:** Technological

Risk Assessment – Mitigation

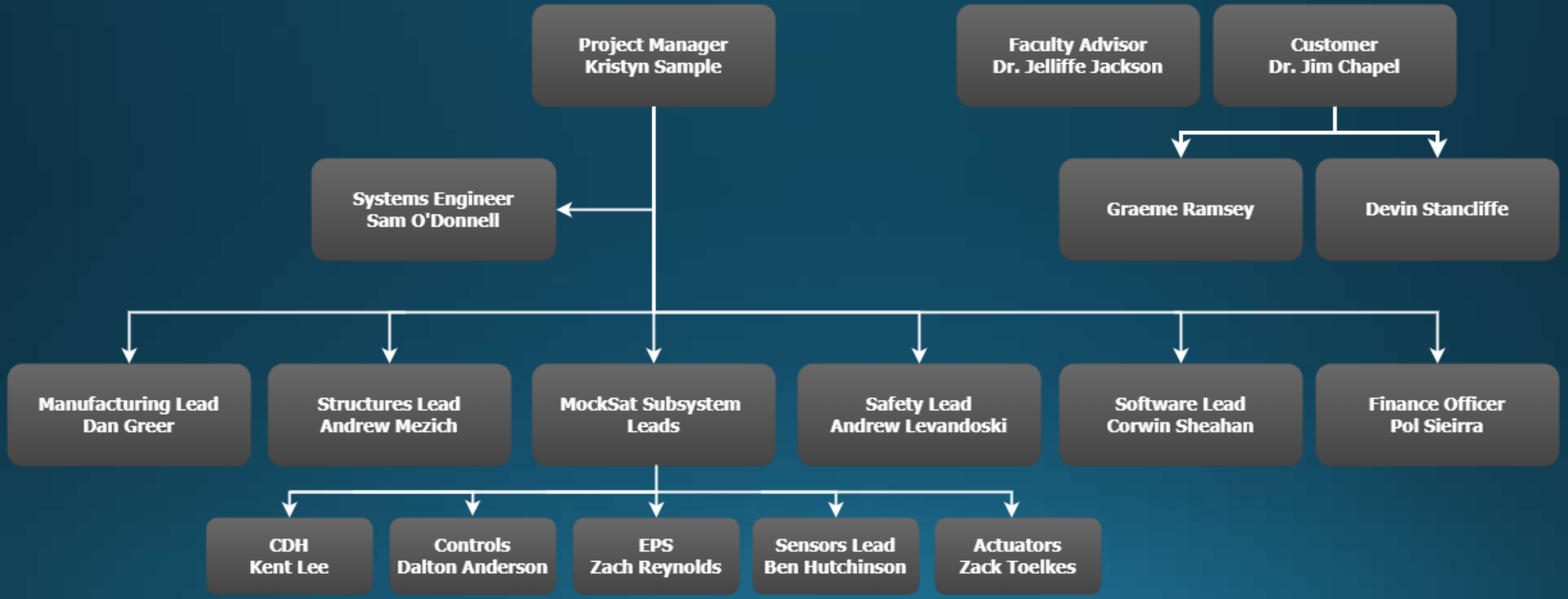
Risk: ADCS Integration		
Cause: Breakdown of communication between any of the ADCS components	**Effect:** ADCS loss of control	
Risk Mitigation		
Action: Careful system integration and understanding of communication protocols	**Success Criteria:** ADCS shares and responds to data as anticipated	**Old Risk Level:** Marginal
		New Risk Level: Acceptable
		Risk Mode: Technological

Risk Assessment – Post-Mitigation

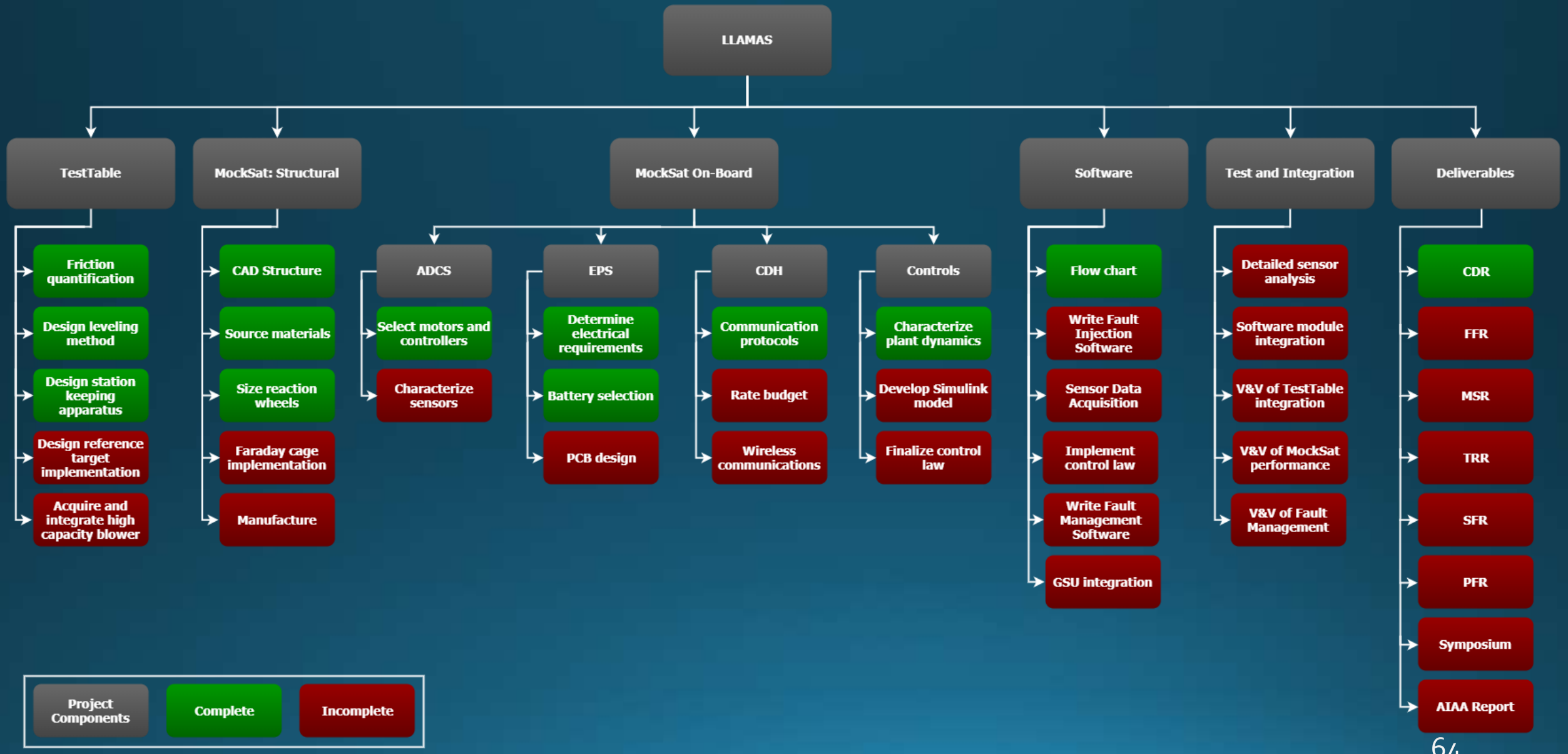
Likelihood	Risk Matrix					
	Very Likely					
	Likely					
	Possible					
	Unlikely				1	2
	Very Unlikely				3	
	Acceptable	Negligible	Minor	Moderate	Significant	Severe
	Marginal					
	Unacceptable	Severity				

1. Lack of torque resolution
2. Fault Management Implementation
3. ADCS Integration

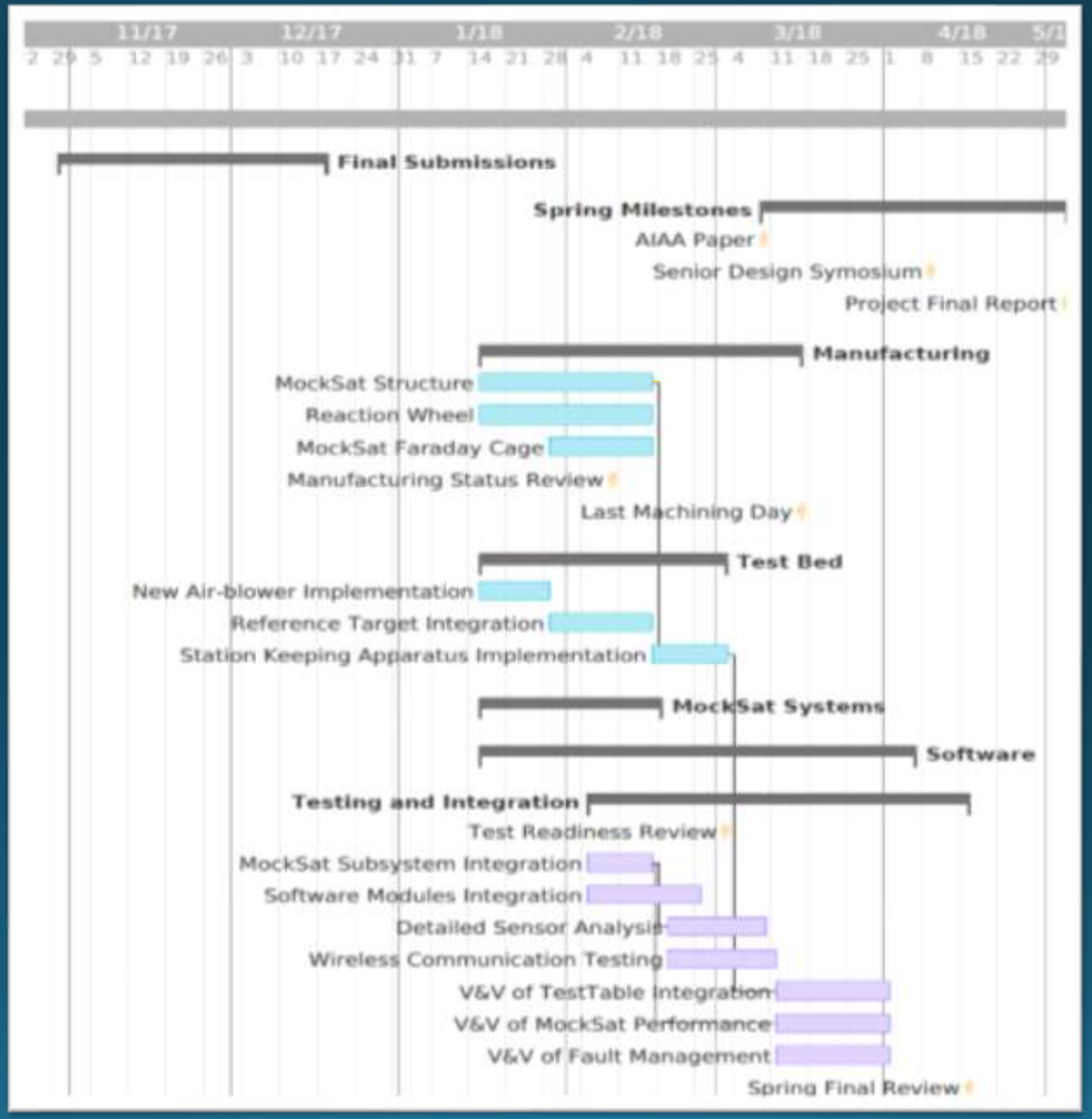
Organizational Chart



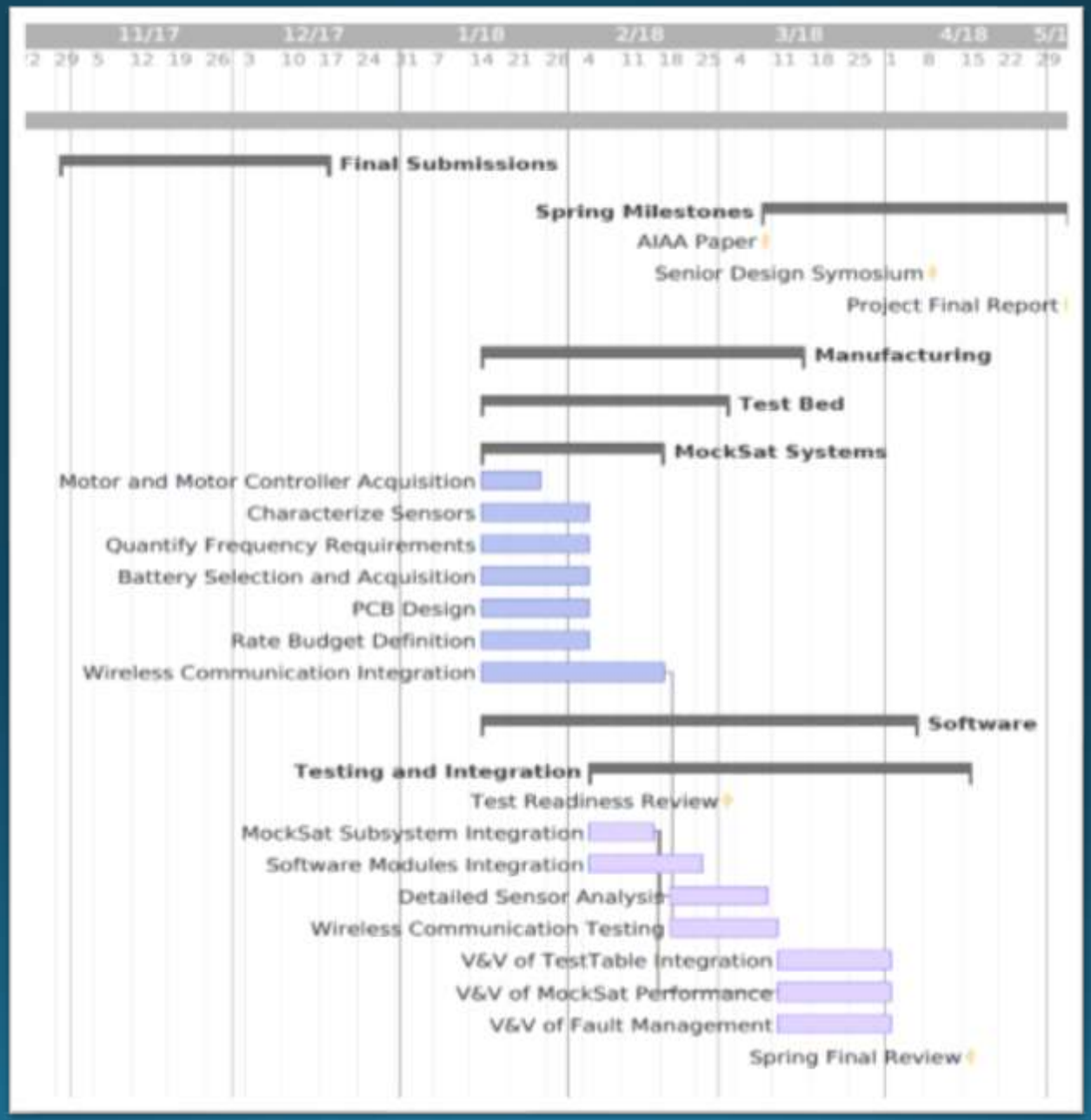
Work Breakdown Structure



Work Plan


11/17
12/17
1/18
2/18
3/18
4/18
5/1
Final Submissions
Spring Milestones
AIAA Paper
Senior Design Symosium
Project Final Report
Manufacturing
MockSat Structure
Reaction Wheel
MockSat Faraday Cage
Manufacturing Status Review
Last Machining Day
Test Bed
New Air-blower Implementation
Reference Target Integration
Station Keeping Appiaratus Implementation
MockSat Systems
Software
Testing and Integration
Test Readiness Review
MockSat Subsystem Integration
Software Modules Integration
Detailed Sensor Analysis
Wireless Communication Testing
V&V of TestTable Integration
V&V of MockSat Performance
V&V of Fault Management
Spring Final Review

Work Plan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PCB Design
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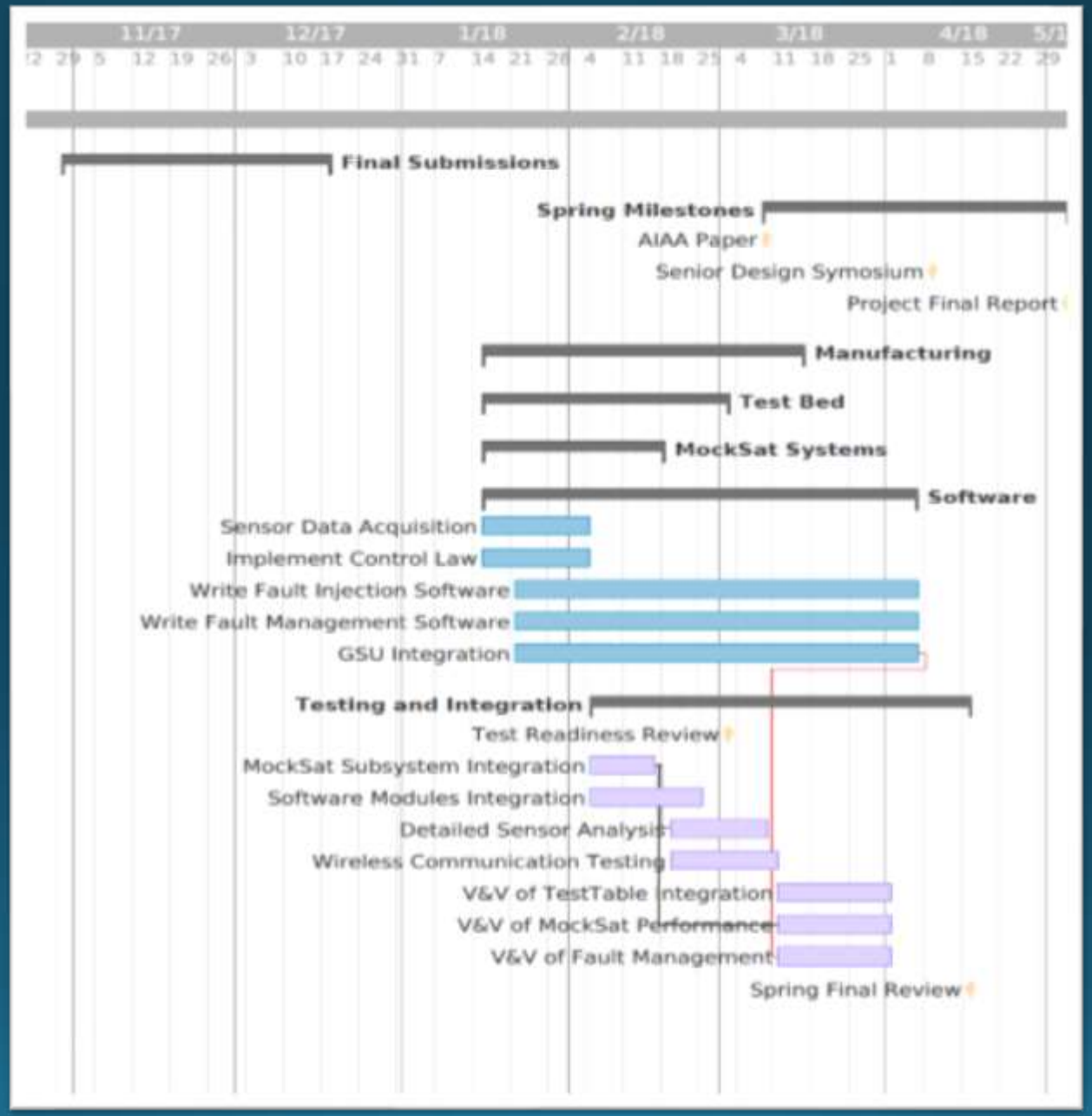
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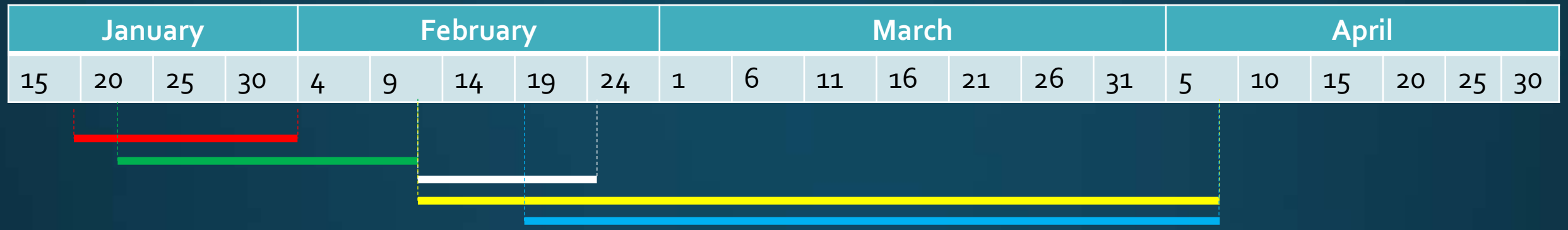
Test Plan



TestTable; 1.3, 1.4
Testable, Source, Fan, Station Keeping Structure

Testing Suite; 1.1, 1.2, 1.3
Completed TestTable and MockSat

Fault Management; 5.1
Testing Suite w/link to ground Station, Fault Injection Software

MockSat; 2.1,2.2
MockSat, Pixies, Reaction Wheels, Elec. Suit

Fault Injection; 4.1, 4.2, 4.3
Testing Suite w/link to ground station

All test will be run in the Lockheed Martin Projects room, and have no restrictions to access.

Cost Plan

EXPENSE BUDGET

LLAMAS

Expense	Category	Expense Amount	Budget Remaining	Margin (%)
			$ 5,000.00	100%
Motor	Actuators	$ 397.76	$ 4,602.24	92%
Motor Controller	Actuators	$ 352.06	$ 4,250.18	85%
Xbee	Communication	$ 40.00	$ 4,210.18	84%
Atmel SAM E70	Microcontroller	$ 50.00	$ 4,160.18	83%
PCB	Power	$ 200.00	$ 3,960.18	79%
Battery	Power	$ 43.68	$ 3,916.50	78%
Murata PS MEJ2S1205SC	Power	$ 10.15	$ 3,906.35	78%
Murata PS MEJ2S1203SC	Power	$ 10.15	$ 3,896.20	78%
Pixy Camera (x3)	Sensors	$ 250.00	$ 3,646.20	73%
IMU	Sensors	$ 50.00	$ 3,596.20	72%
Encoder	Sensors	$ 174.50	$ 3,421.70	68%
Encoder Interface	Sensors	$ 572.96	$ 2,848.74	57%
Reference Source	Sensors	$ 60.00	$ 2,788.74	56%
Raw Materials	Structure	$ 500.00	$ 2,288.74	46%
Wiring	Structure	$ 150.00	$ 2,138.74	43%
Totals		$ 2,861.26	$ 2,138.74	43%

Questions?

Backup Slides

TestTable

Design Requirements and Satisfaction - TestTable

CONOPs: Quantify 5mm/s target speed

Baseline Design - TestTable

ADCS: Station Keeping

CDH

Avionics Schematic

EPS

MockSat EPS Comparisons

MockSat EPS (Voltage Regulator)

MockSat EPS (DC-DC Converter)

MockSat EPS: Battery Selection

ADCS

Design Requirements and Satisfaction – MockSat Controls

Verification and Validation – Pointing Accuracy

Design Requirements and Satisfaction – Motor Selection

Design Requirements and Satisfaction – Motor Controller

Attitude Control: Motors

Attitude Control: Motor Controller

Design Solution – MockSat Reaction Wheels

Attitude Control: Sensors

Sensors -Pixy Specs

Software

Software: Main Loop

Fault Management

Software: Class Diagram

Reaction Wheel Friction

Fault Management Interface

Structures

Structural Analysis - Standoffs

Structural Analysis - Plates

Structures BoM

Requirements Flow-Down

Design Requirements and Satisfaction - TestTable

- Redefinition of FR 1.3.1
  - Quantification of losses (friction) inherent to the TestTable as a whole, including station-keeping apparatus.
- Station keeping method, FR 1.2.1
- Reference target motion, FR 3.0

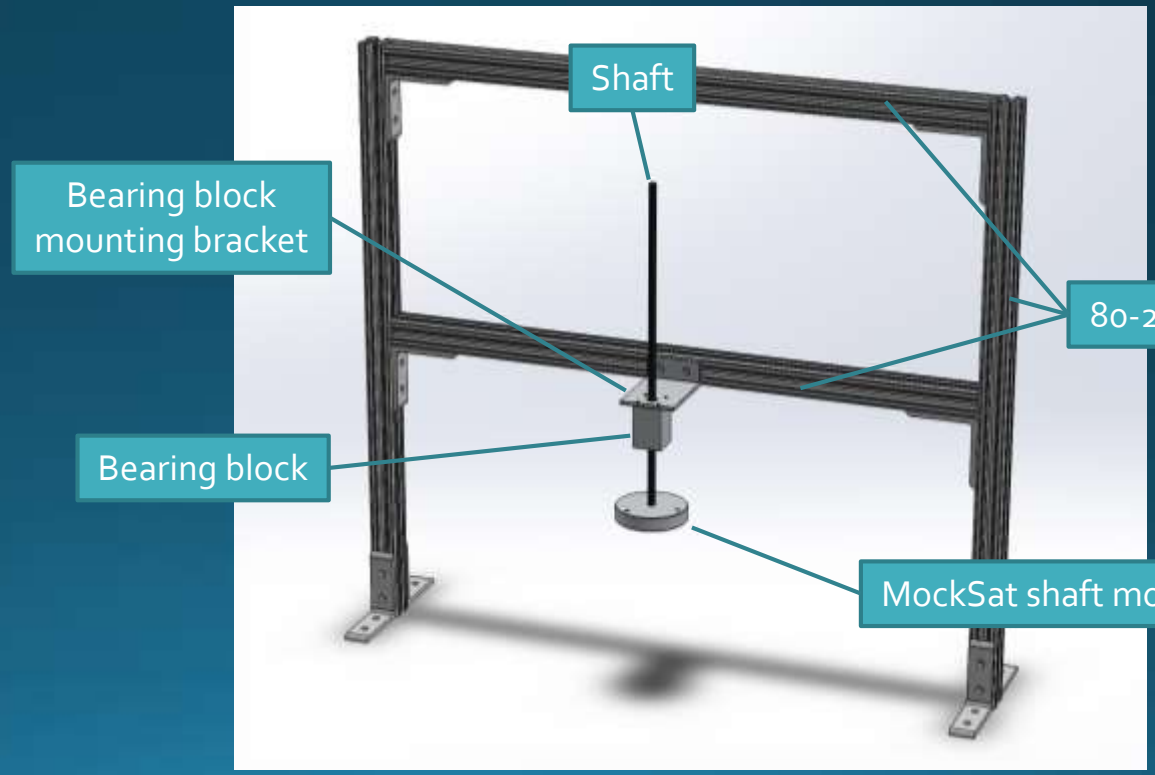
FR 1.3.1 – ~~The maximum frictional force between the MockSat and the TestTable during operation shall be no greater than 1% of the maximum frictional force between a block of a representative MockSat material (i.e. aluminum) of a similar mass as the MockSat and a plate of a representative (i.e. polycarbonate).~~

FR 1.3.1 – *The coefficient of total rotational friction between the MockSat and the TestTable during nominal operation shall be no greater than* $1.5\ \frac{lbm \cdot in^2}{s}$ *.*

Design Requirements and Satisfaction - TestTable

- Redefinition of FR 1.3.1
  - Quantification of losses (friction) inherent to the TestTable as a whole, including station-keeping apparatus.
- Station keeping method, FR 1.2.1
- Reference target motion, FR 3.0

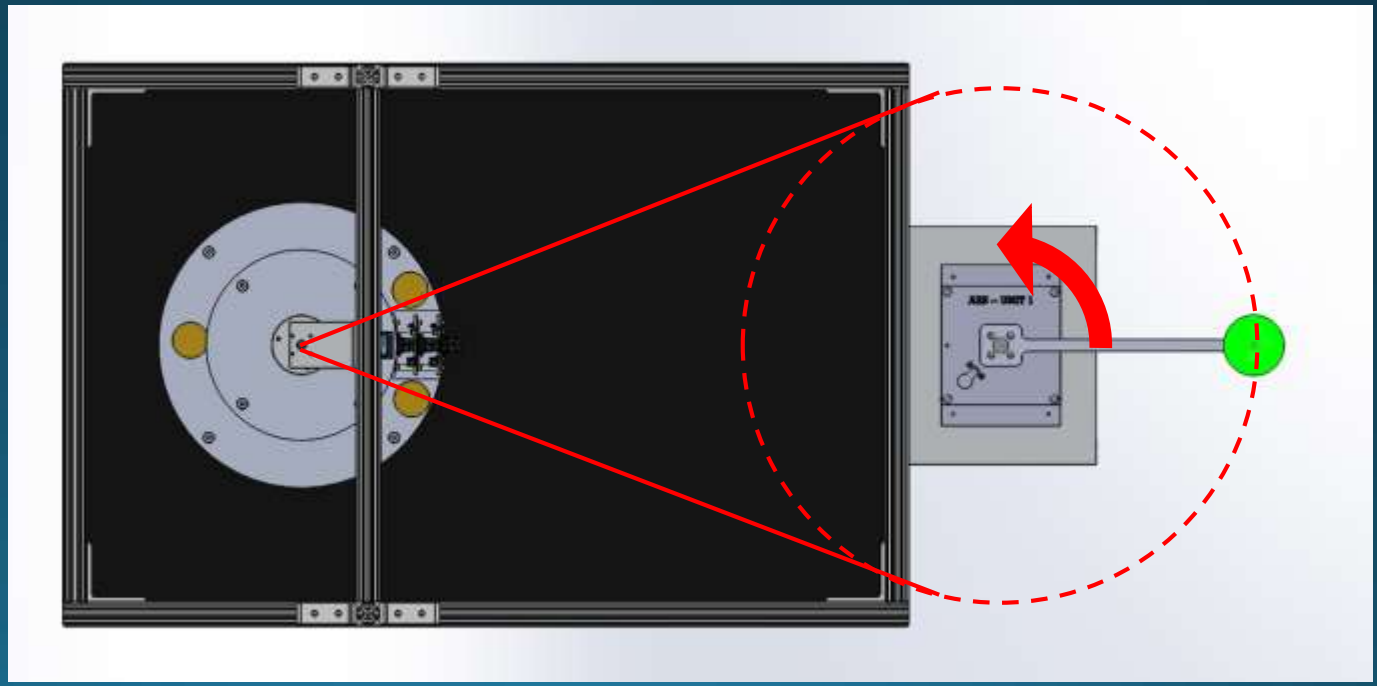
- *Bearing block and bracket supported by 80-20 framework.*
- *Steel shaft rigidly fixed to MockSat upper surface such that the shaft is collinear with the z-axis of inertia.*
- *Slip-fit shaft allows MockSat to rise off TestTable surface.*



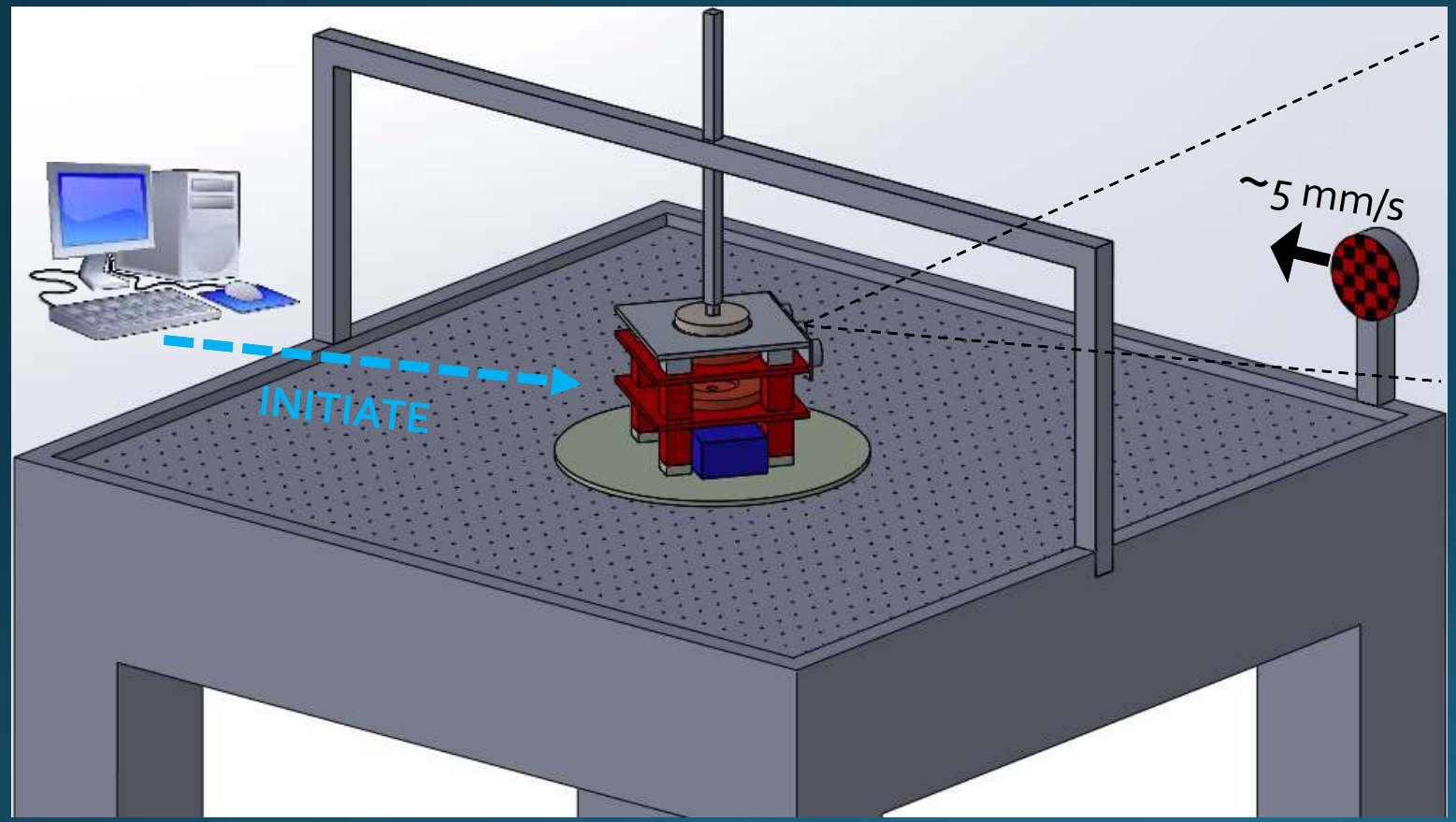
Design Requirements and Satisfaction - TestTable

- Redefinition of FR 1.3.1
  - Quantification of losses (friction) inherent to the TestTable as a whole, including station-keeping apparatus.
- Station keeping method, FR 1.2.1
- Reference target, FR 3.0

- *Provides verification of the ±2.5° pointing requirement.*
- *Inherently sinusoidal from the perspective of the MockSat.*
- *Design based off of ASEN 2003 control arm module outfitted with a rigid arm. A battery-operated LED bulb is attached to the end of rigid arm; this is the object the MockSat tracks.*



CONOPs: Quantify 5mm/s target speed



From bandwidth requirement

$$\tau = \frac{1}{2\pi f_b} = \frac{1}{2\pi(0.04)} \approx 4\ s$$

Can get a representative

$$\omega_{avg} = \frac{0.63\theta_c}{\tau} = \frac{0.63\left(75\frac{\pi}{180}\right)}{\tau} \approx 0.2\ \frac{rad}{s}$$

The radius is known, therefore

$$v_{max} = \omega_{avg} r_{max} \approx 10\ \frac{cm}{s}$$

Dropping 1.5 orders of magnitude

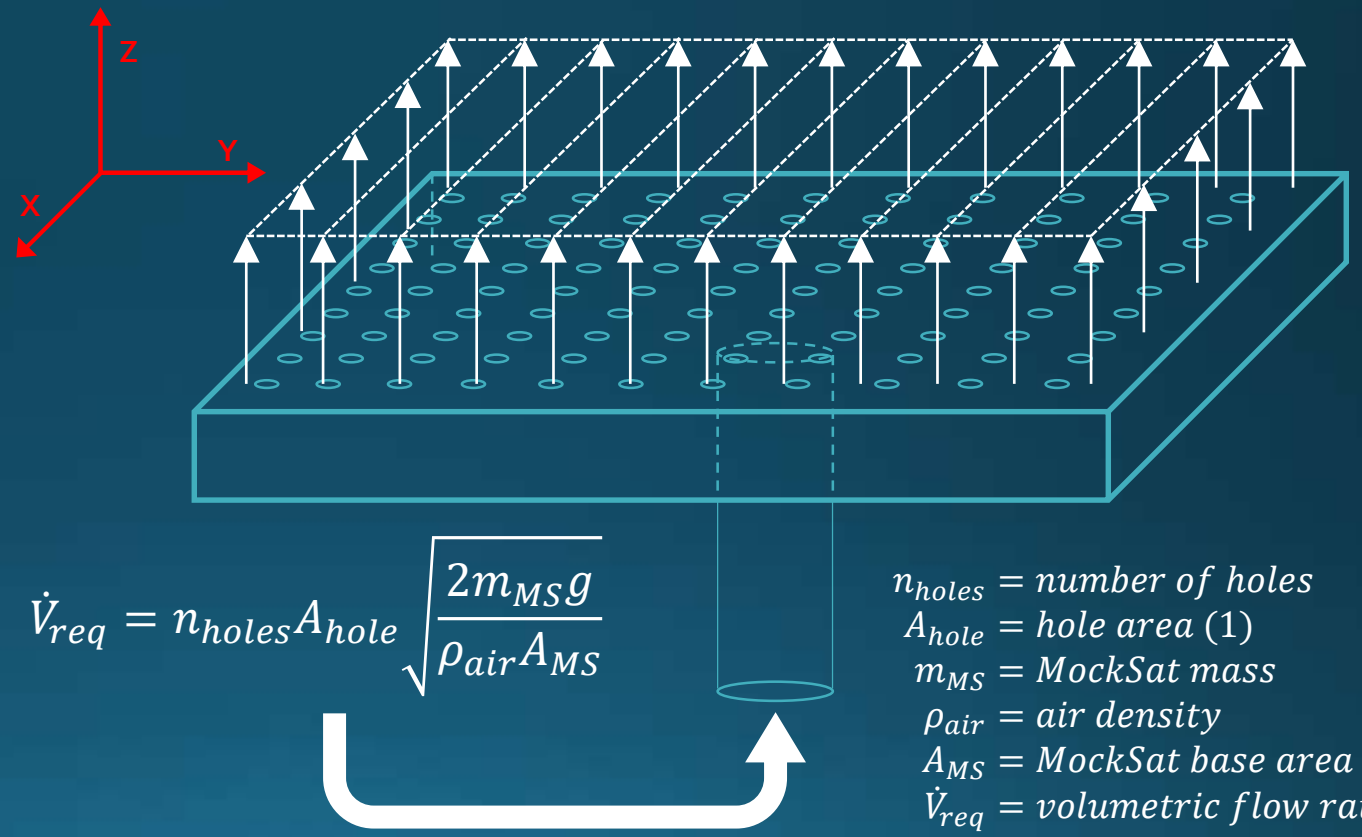
$$v_{target} \approx 5\ \frac{mm}{s}$$

Baseline Design – TestTable

Functional Requirement: *The TestTable shall provide for 3DOF dynamics in a reduced-friction environment.*

Air table:

- Creates a cushion of air under the MockSat by forcing air through small holes in the table perpendicular to the table surface.
- By raising the MockSat off the table surface, friction is drastically reduced.
- Allows for translation in [X,Y] and rotation about [Z].



$$\dot{V}_{req} = n_{holes} A_{hole} \sqrt{\frac{2 m_{MS} g}{\rho_{air} A_{MS}}}$$

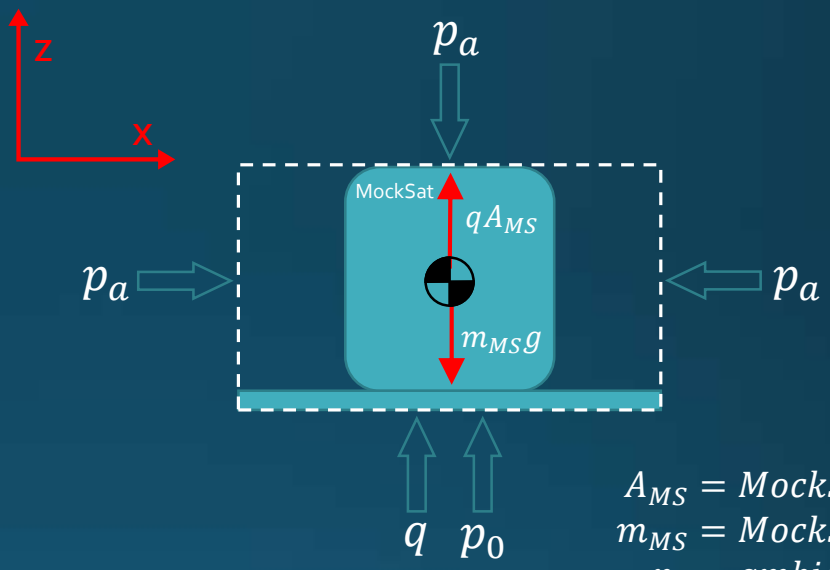
$n_{holes} = number\ of\ holes$
$A_{hole} = hole\ area\ (1)$
$m_{MS} = MockSat\ mass$
$\rho_{air} = air\ density$
$A_{MS} = MockSat\ base\ area$
$\dot{V}_{req} = volumetric\ flow\ rate$

Baseline Design – TestTable

Functional Requirement: *The TestTable shall provide for 3DOF dynamics in a reduced-friction environment.*

Air table:

- Assumptions: steady, incompressible flow.
- Dynamic pressure of air flowing through the table and impacting the underside of the MockSat provides the force to lift the MockSat off the table surface.
- The pressure difference between the static pressure of the air source and ambient is assumed to be small, therefore $p_0 \cong p_a$.



$A_{MS} = MockSat\ base\ area$
$m_{MS} = MockSat\ mass$
$p_0 = ambient\ pressure$
$p_0 = air\ source\ static\ pressure$
$q = dynamic\ pressure$

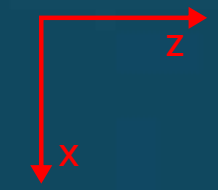
$$\sum F_x = (p_0 - p_0)A_x = 0$$

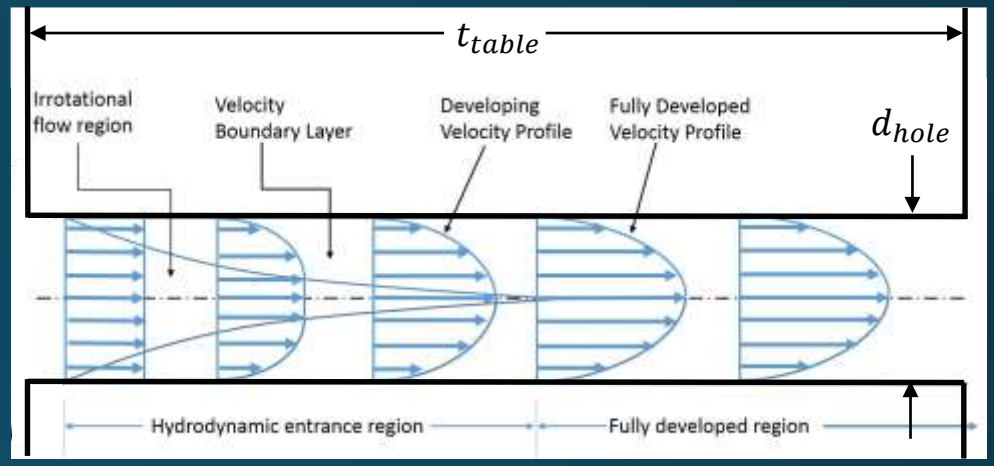
$$\sum F_y = (p_0 - p_0)A_y = 0$$

$$\sum F_z = (\cancel{p_0} + q - \cancel{p_0})A_z = qA_z = mg$$

Baseline Design – TestTable

Functional Requirement: *The TestTable shall provide for 3DOF dynamics in a reduced-friction environment.*





By DEVENDER KUMAR5908 - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=33253407

Investigation of potential losses:

- Boundary layer formation
  - The hydrodynamic entry length $L_h \cong 37.5$" is much greater than the thickest table material being considered ($1/2$" polycarbonate plastic).
  - Therefore the flow can be assumed to be uniform.
- MockSat cg location
  - A couple moment will be introduced if the cg of the MockSat is not positioned over the geometric center of the MockSat baseplate.
  - This will cause the MockSat to move in the direction of the cg displacement.
  - Bounding translation resolves this issue.
- Irregular surfaces
  - The thickness of the air cushion will determine manufacturing tolerances for making the table surface and underside of the MockSat flat.

$$Re = \frac{\rho u L}{\mu} \rightarrow \frac{\rho_{air}\left(\sqrt{\frac{2m_{MS}g}{\rho_{air}A_{MS}}}\right)t_{table}}{\mu_{air}} \quad \text{for } t_{table} = \frac{1}{2}"$$

$$L_{h,laminar} = .05(Re)d_{hole} \cong 37.5" \quad \text{for } d_{hole} = \frac{1}{32}"$$

Baseline Design – TestTable

Functional Requirement: *The TestTable shall provide for 3DOF dynamics in a reduced-friction environment.*

<u>Investigation of potential losses:</u>

- Boundary layer formation
  - The hydrodynamic entry length $L_h \cong 37.5$” is much greater than the thickest table material being considered ($1/2$ ” polycarbonate plastic).
  - Therefore the flow can be assumed to be uniform.
- MockSat cg location
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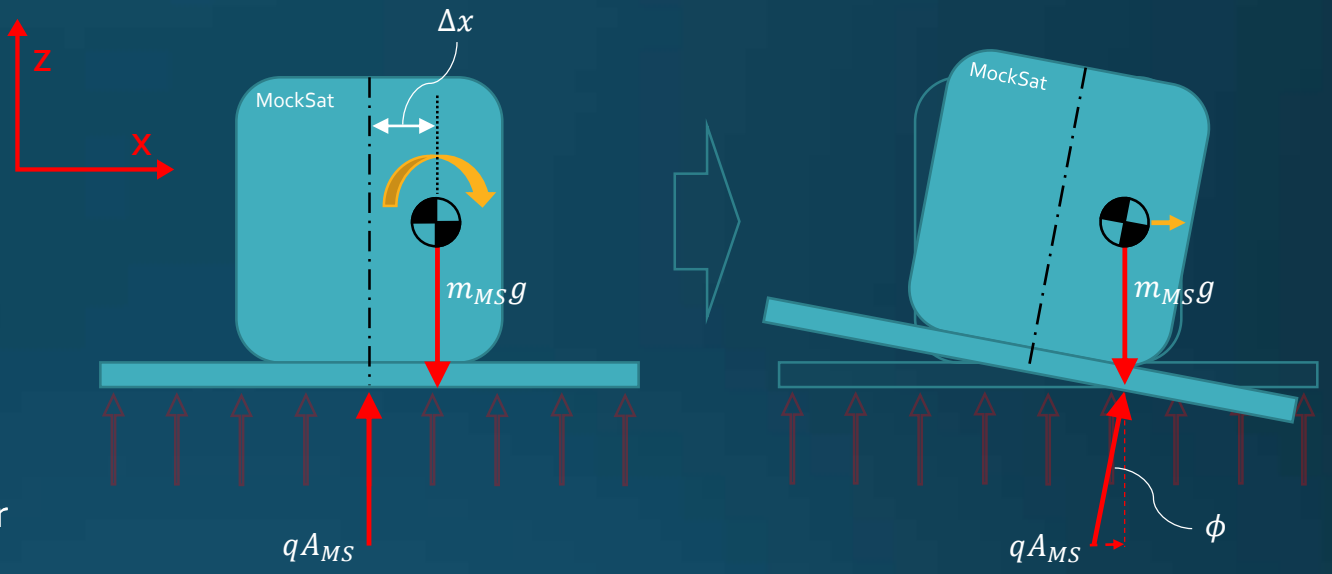
- Irregular surfaces
  - The thickness of the air cushion will determine manufacturing tolerances for making the table surface and underside of the MockSat flat.



$$\sum F_x \rightarrow 0$$

$$\sum F_z \rightarrow qA_{MS} = m_{MS}g$$

$$\sum M_{cg} \rightarrow m_{MS}g(\Delta x)$$

$$\sum F_x \rightarrow qA_{MS}\sin\phi = m_{MS}a_x$$

$$\sum F_z \rightarrow qA_{MS}\cos\phi = m_{MS}g$$

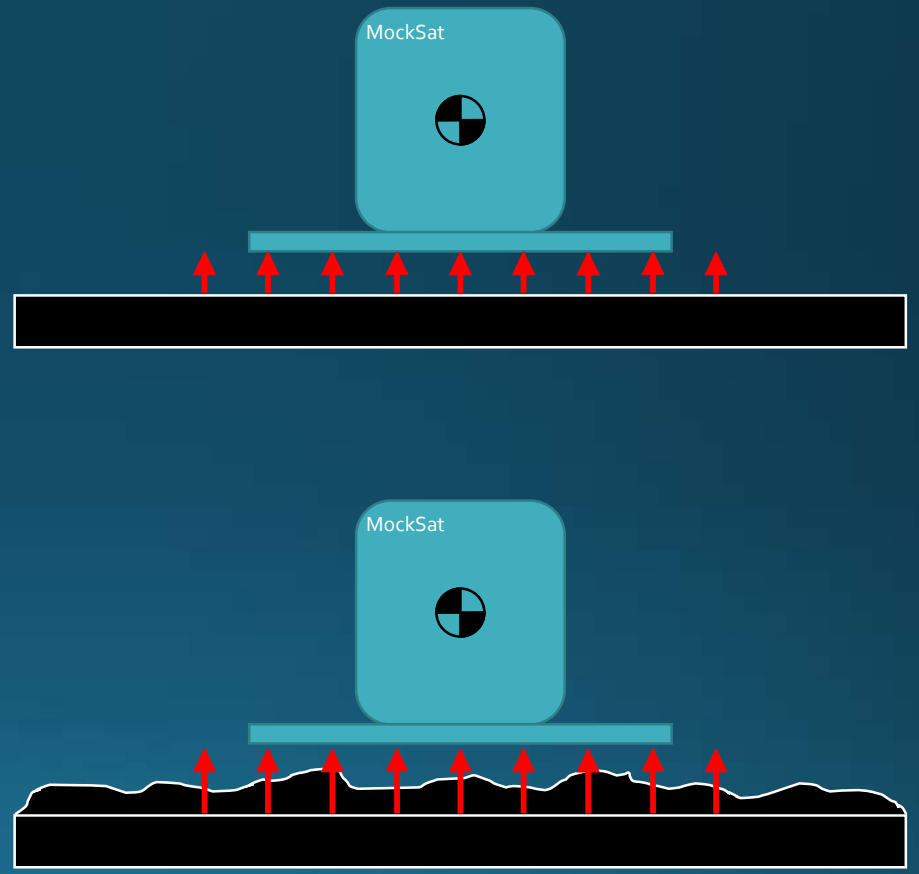
$$\sum M_{cg} \rightarrow 0$$

Baseline Design – TestTable

Functional Requirement: *The TestTable shall provide for 3DOF dynamics in a reduced-friction environment.*

<u>Investigation of potential losses:</u>

- Boundary layer formation
  - The hydrodynamic entry length $L_h \cong 37.5$" is much greater than the thickest table material being considered ($1/2$ " polycarbonate plastic).
  - Therefore the flow can be assumed to be uniform.
- MockSat cg location
  - A couple moment will be introduced if the cg of the MockSat is not positioned over the geometric center of the MockSat baseplate.
  - This will cause the MockSat to move in the direction of the cg displacement.
  - Bounding translation resolves this issue.
- Irregular surfaces
  - The thickness of the air cushion will determine manufacturing tolerances for making the table surface and underside of the MockSat flat.

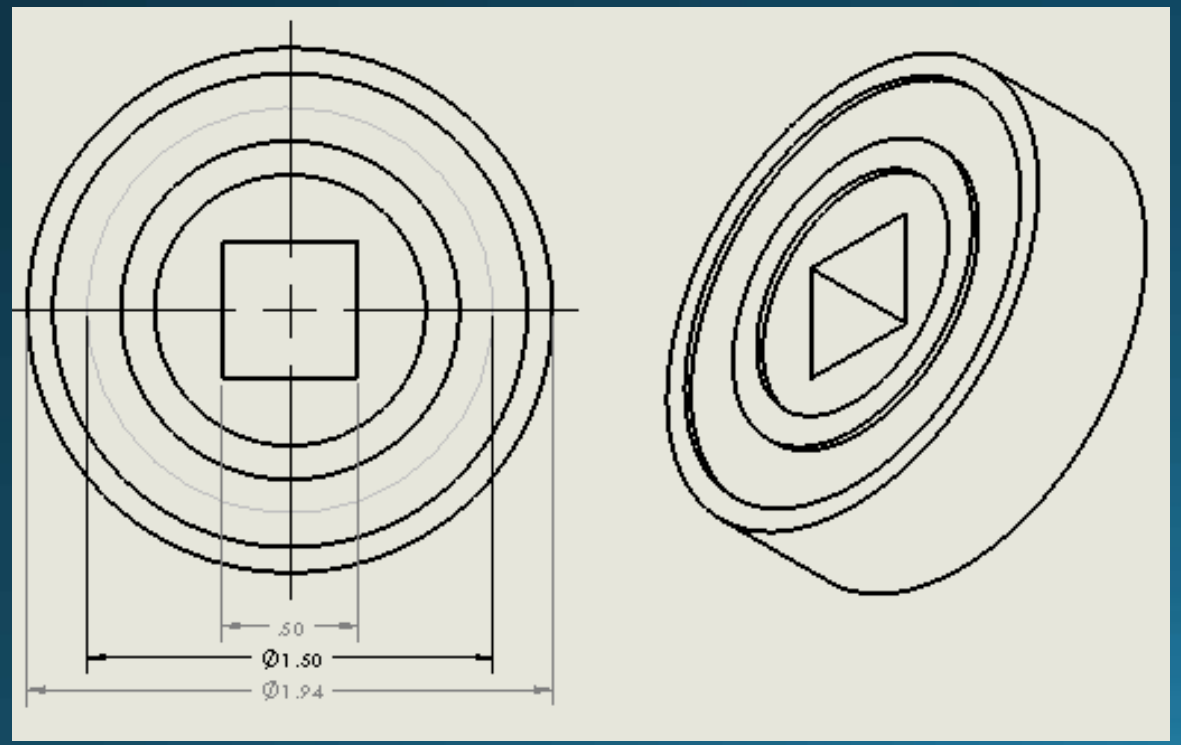


ADCS: Station Keeping

Functional Requirement 3:

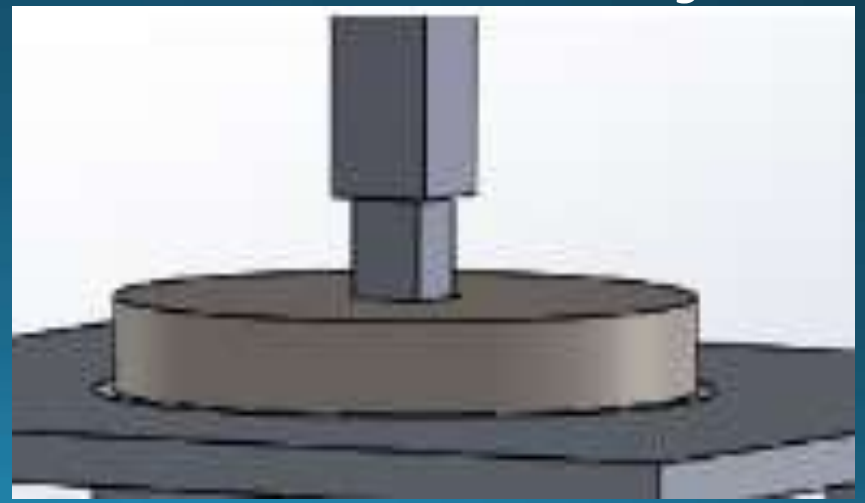
- *The MockSat shall have the ability to maintain a controlled attitude relative to a point of reference within ± 2.5 degrees*

Bearing design

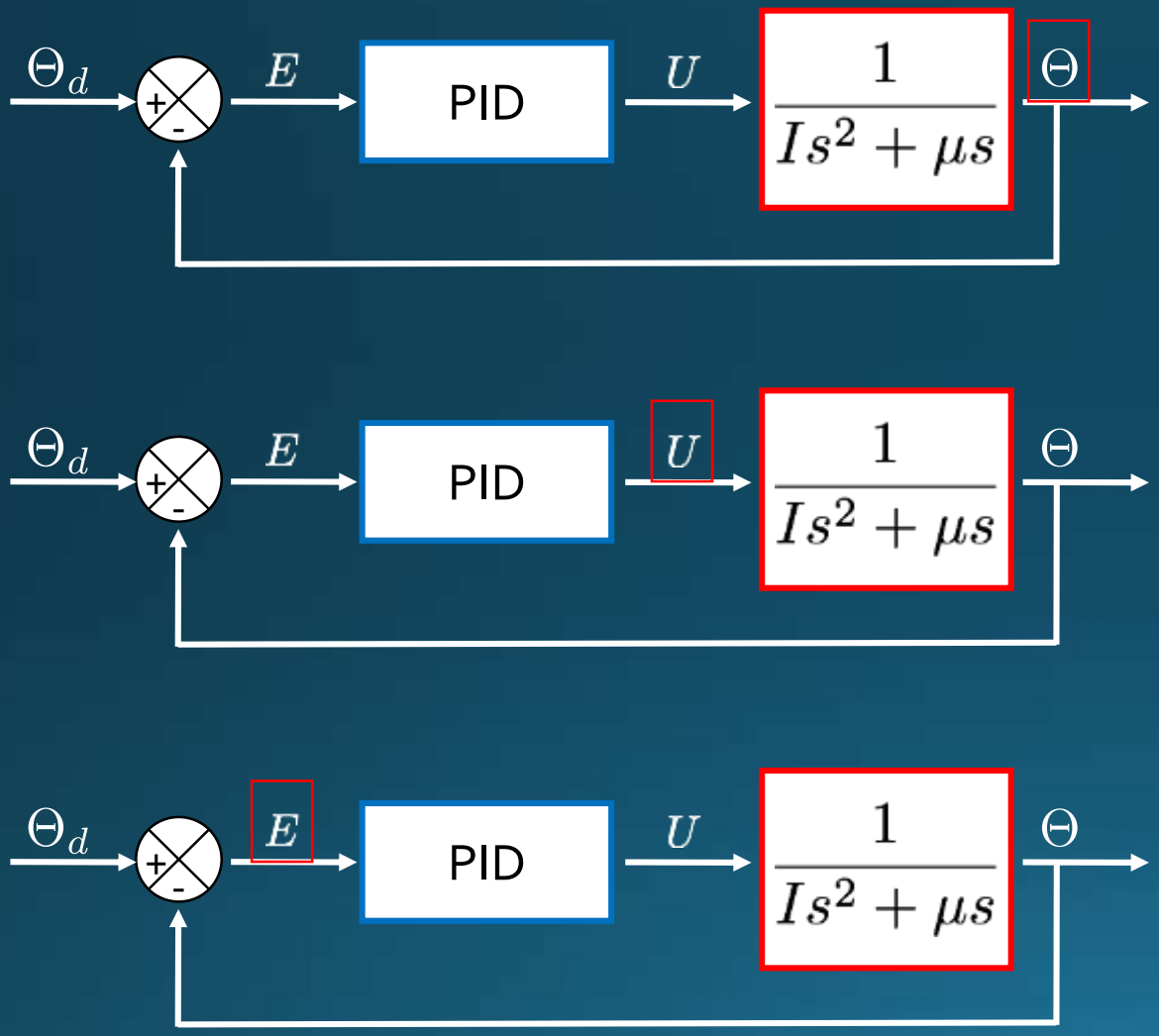


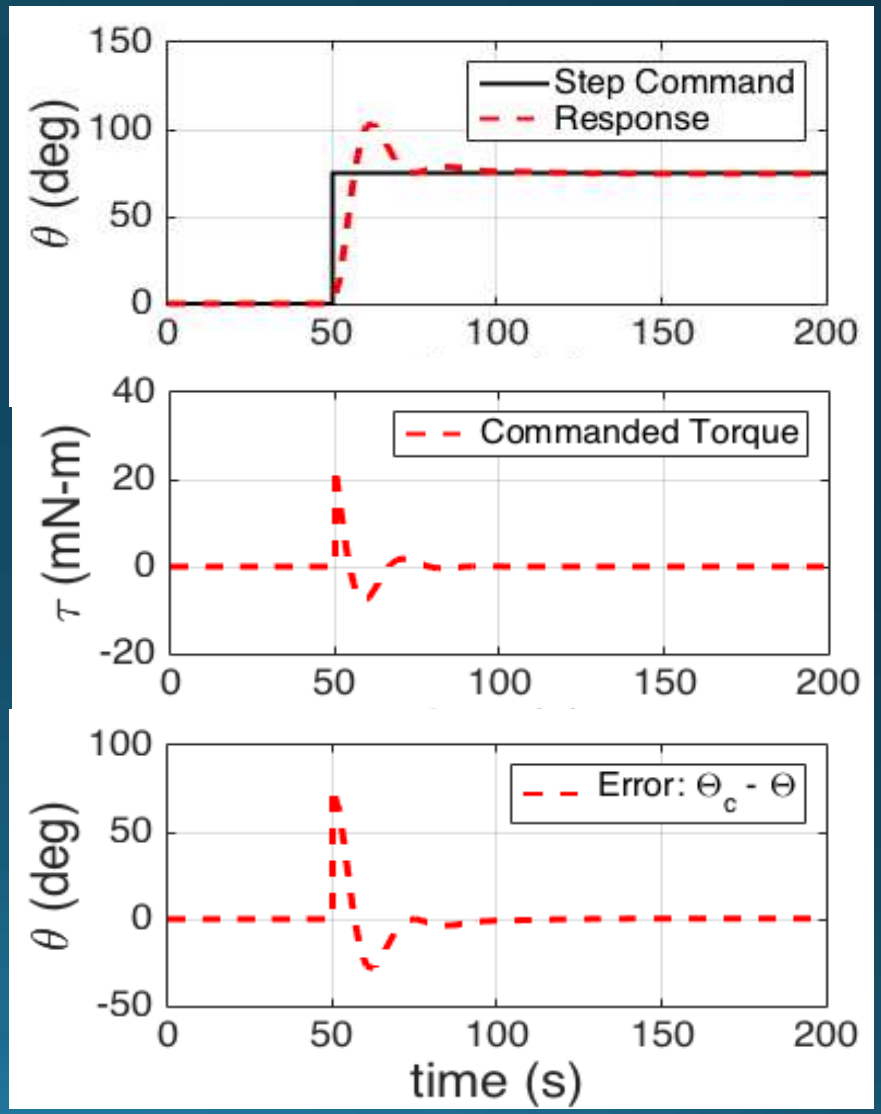
- Purpose of station keeping is to limit translation, focus on rotation dynamics
- Need to keep friction low between bearing and MockSat, maintain rotational dynamics

Rod inserted into bearing

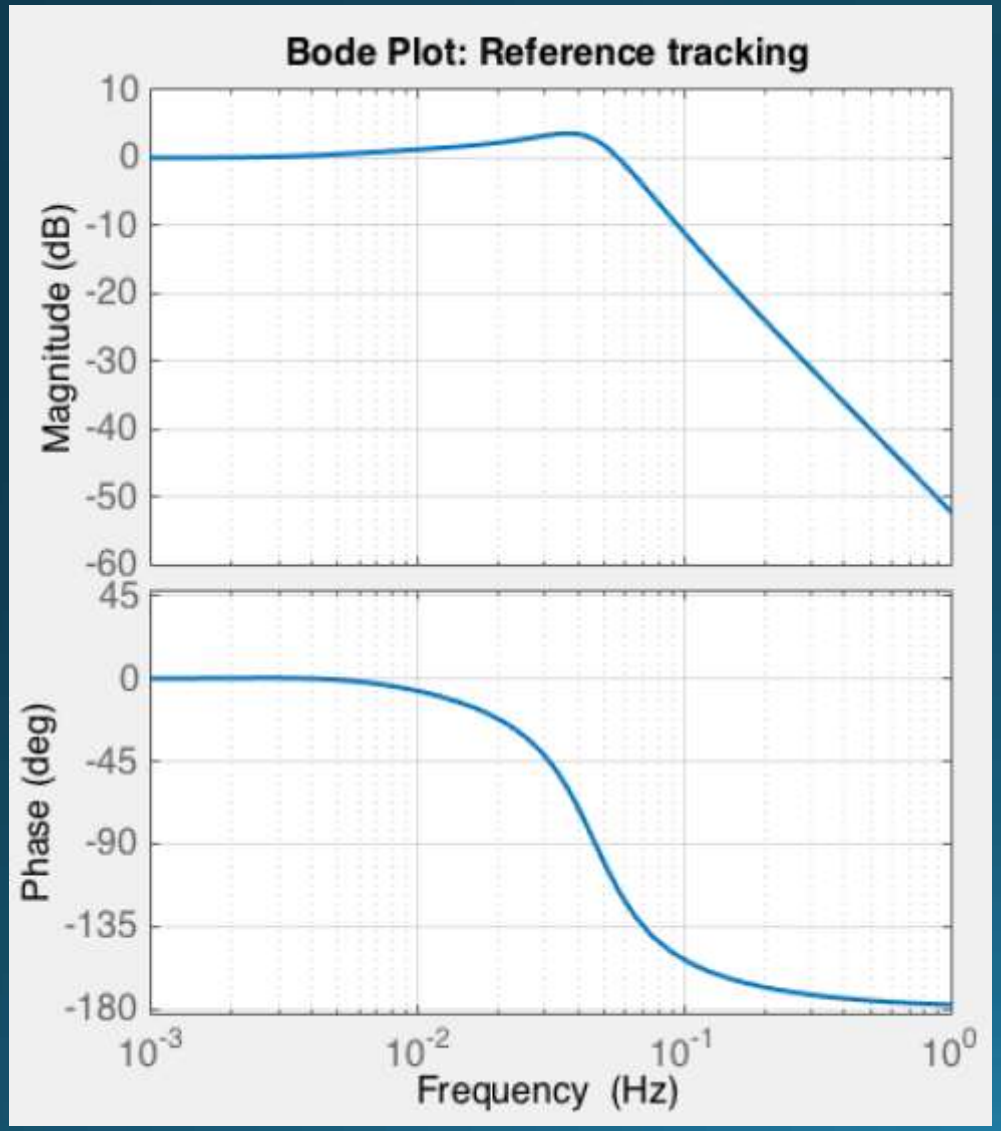


Design Requirements and Satisfaction – MockSat Controls

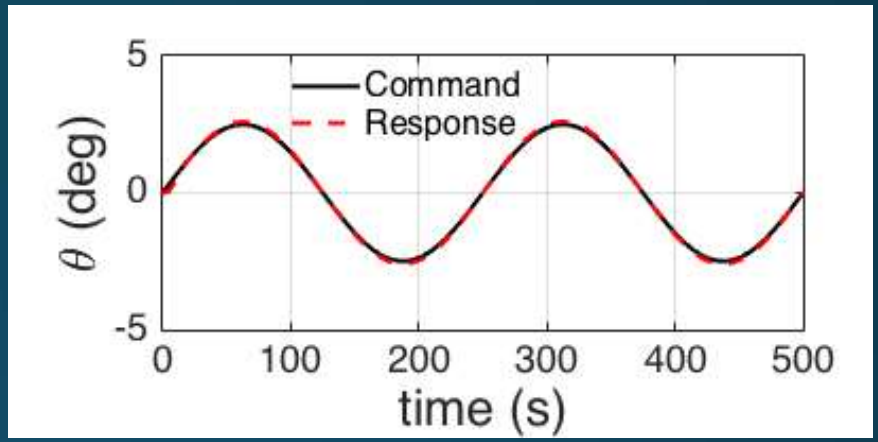




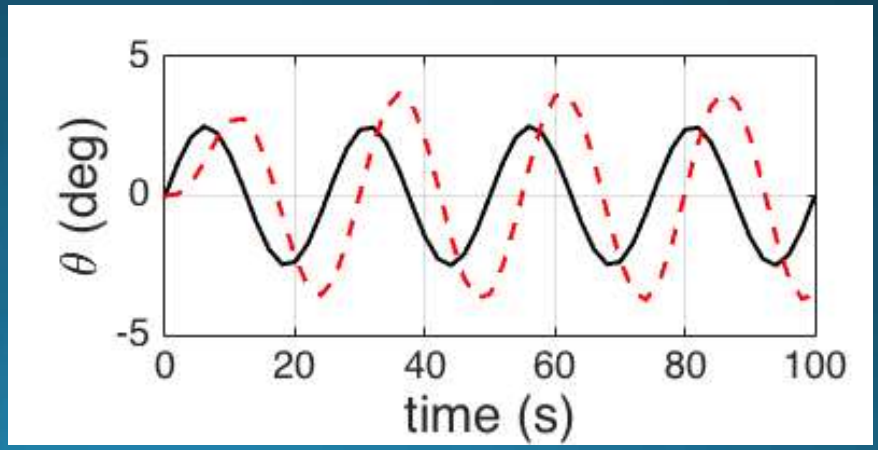
Design Requirements and Satisfaction – MockSat Controls



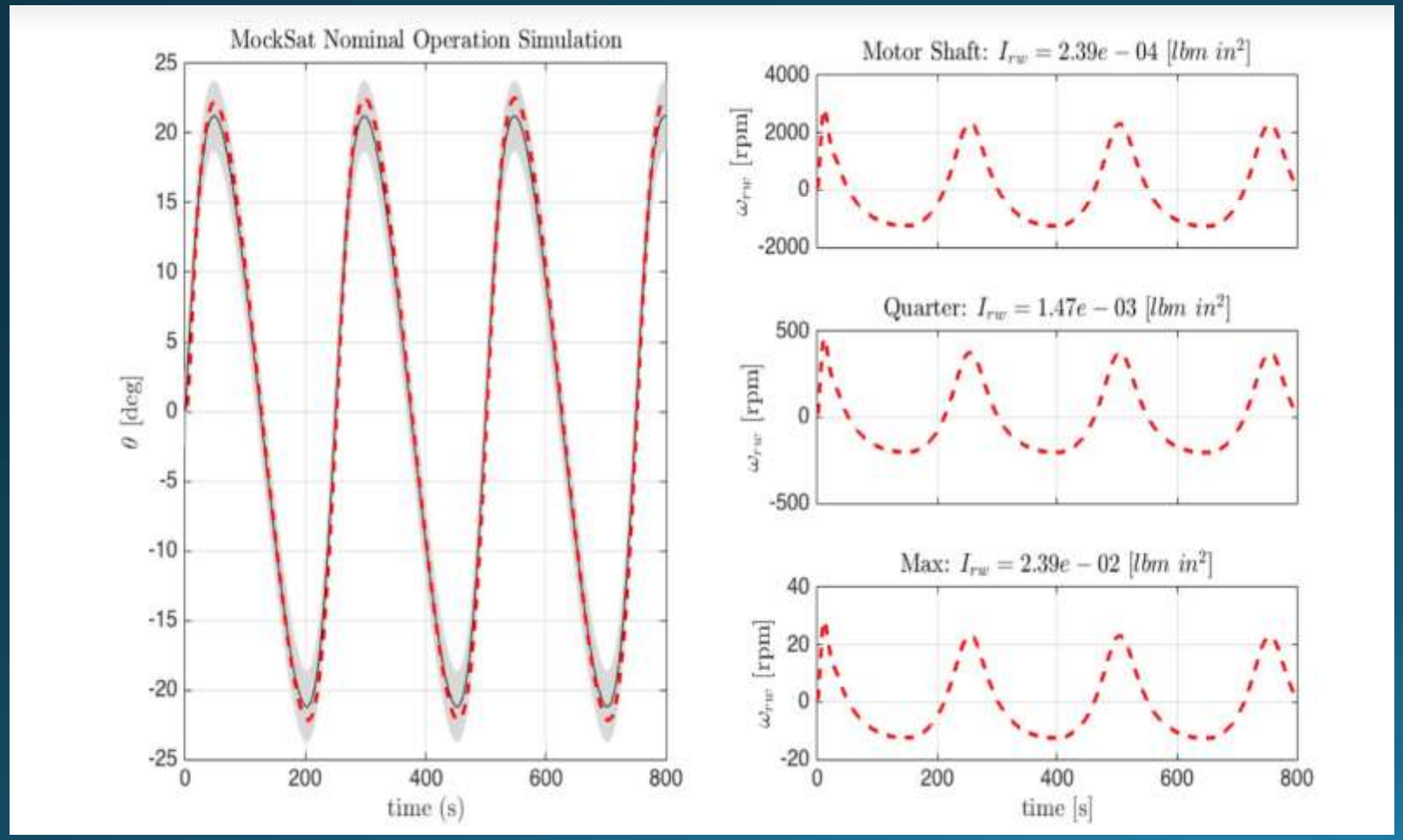
Amplitude = 2.5 degrees
f = 0.004 Hz



Amplitude = 2.5 degrees
f = 0.04 Hz



Design Requirements and Satisfaction – Reaction Wheel Sizing and Motor Selection

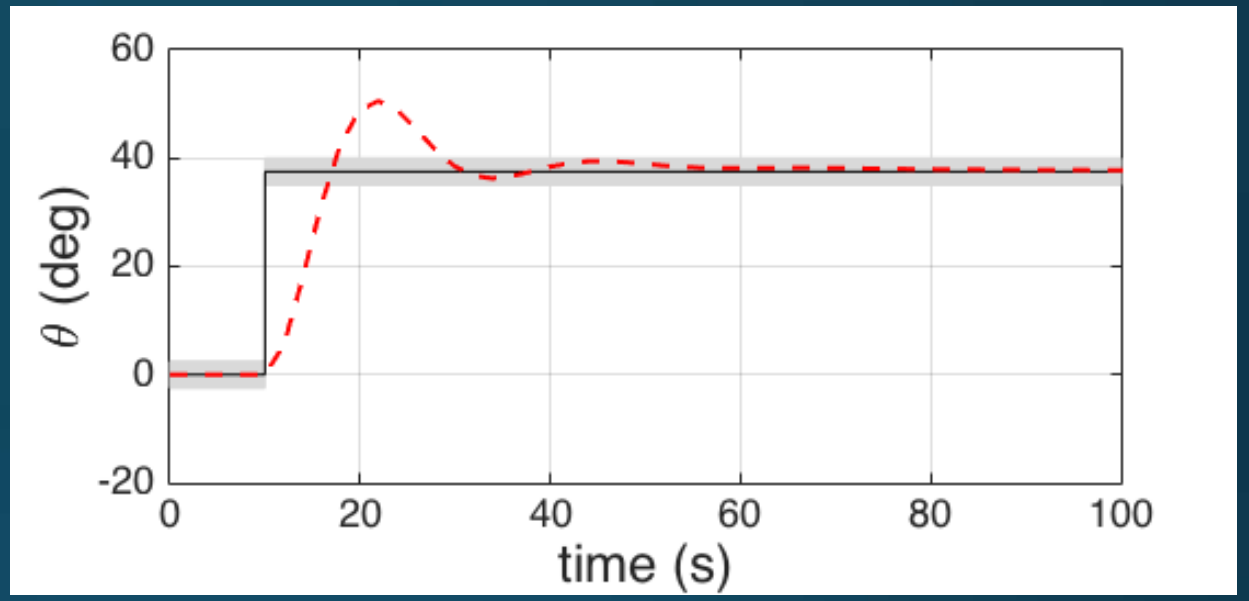


Selected motor will be able to provided necessary velocity for variable reaction wheel inertias

Verification and Validation – Pointing Accuracy

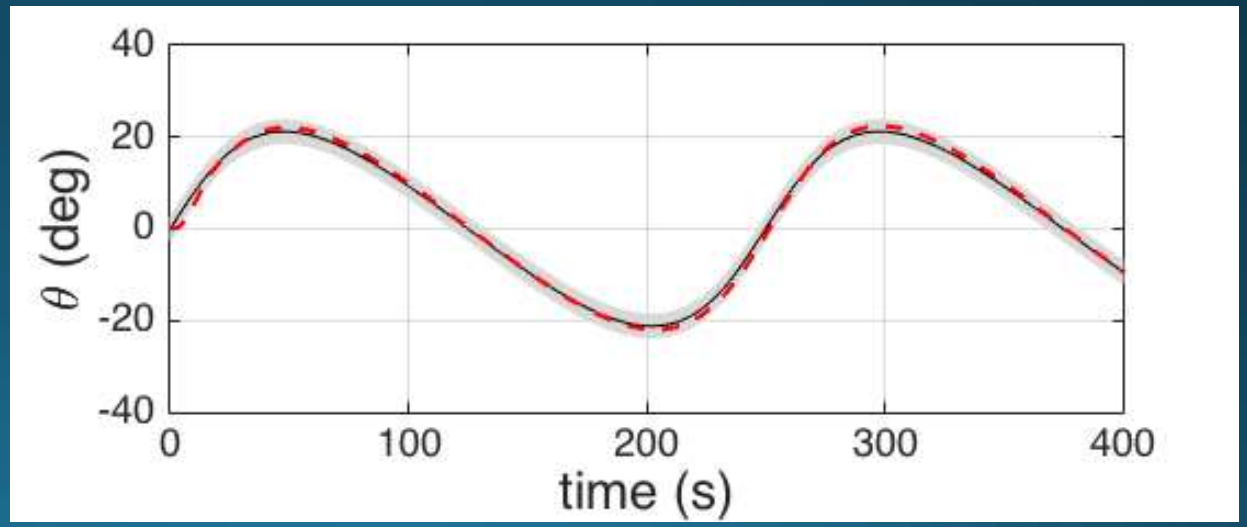
Stationary Target Test

- Modeled by step response
- MockSat identifies target location, rotates to pointing at the target and holds position.

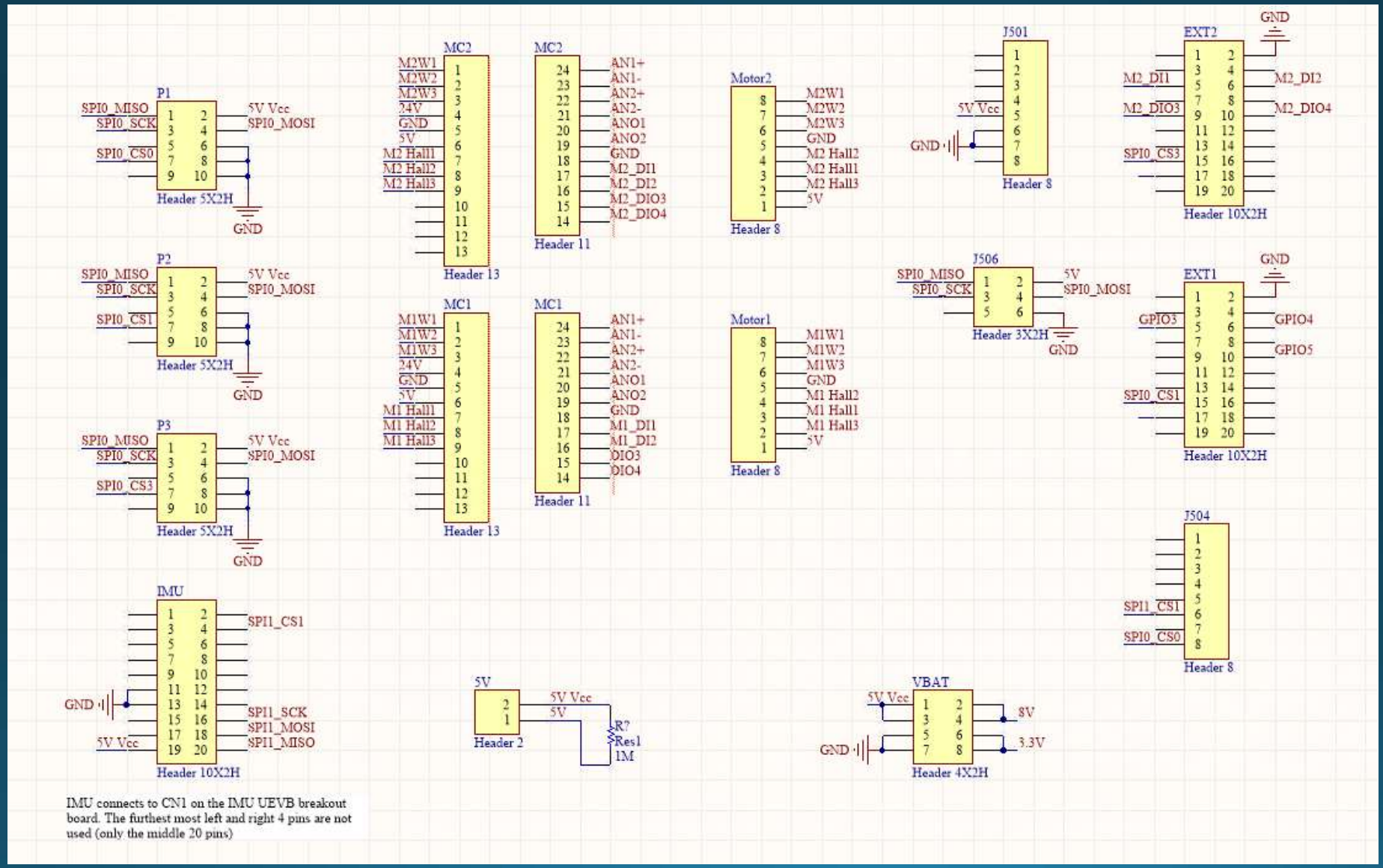


Moving Target Test

- Modeled by target motion pattern
- MockSat identifies target location, and tracks the target in motion.



Avionics Schematic



Design Requirements and Satisfaction – Microcontroller Functionality

- ATMEL SMAE70 XPLD (SAME70Q21)
  - 23-bit ARM Cortex-M7 (144 pin package/ 5 PIO
- 12 MHz Oscillator (300 MHz with PLL)
- 2 SPI channels
- 3 USART channels (SPI configurable)
- FPU (single & double precision)
  - 8 FLOPS per instruction cycle
- 32-bit 2 channel DTCM (Data bus)
- 64 bit ITCM (Instruction bus)

Design Requirements and Satisfaction – SPI Communication

- SPI0 & SPI1
- 4 Chip selects per line
  - Optional: 4-bit to 8-bit decoder (up to 15 chip selects)

Design Requirements and Satisfaction – Motor Selection

Using current I_{ms} and inputting this into the Simulink with a step command of 75° -> outputs a 22 mNm torque (τ_{ms}) needed by the Mocksat (ms) to meet bandwidth response requirements of our system

Assuming $\tau_{ms} = \tau_{rw}$ (rw = reaction wheel)

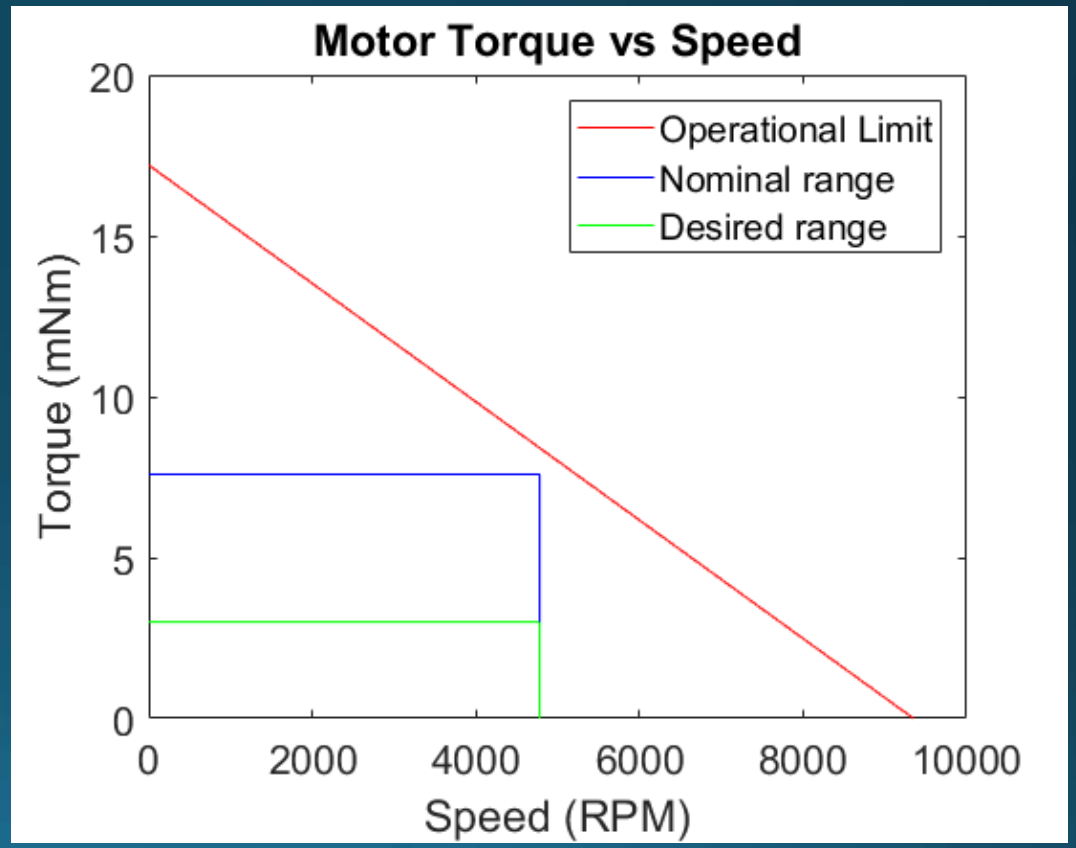
- $\tau_{ms} = \tau_{rw} = I_{rw}\alpha_{rw}$ $\qquad$ $I_{rw} = \frac{1}{2}mr^2$
- Solving for α_{rw} and multiplying by pixie command time ~20ms gives an ω_{rw}
- Finding an ω_{rw} that falls within the torque gradient curve for motor allows us to pick a motor for the MockSat

Design Requirements and Satisfaction – Motor Controller

- The motor controller selected is: ESCON 24/2
- This is the desired motor controller that works with the motor selected
- Efficiency of this motor controller is: 92% max
- With the required voltage needed to power the motor and accounting for inefficiencies, this falls well within the operating range

Attitude Control: Motors

- 3 mNm step requirement
- Worst case scenario
- Well within tolerances
- VERY conservative
- Options for smaller torque/speed operational ranges

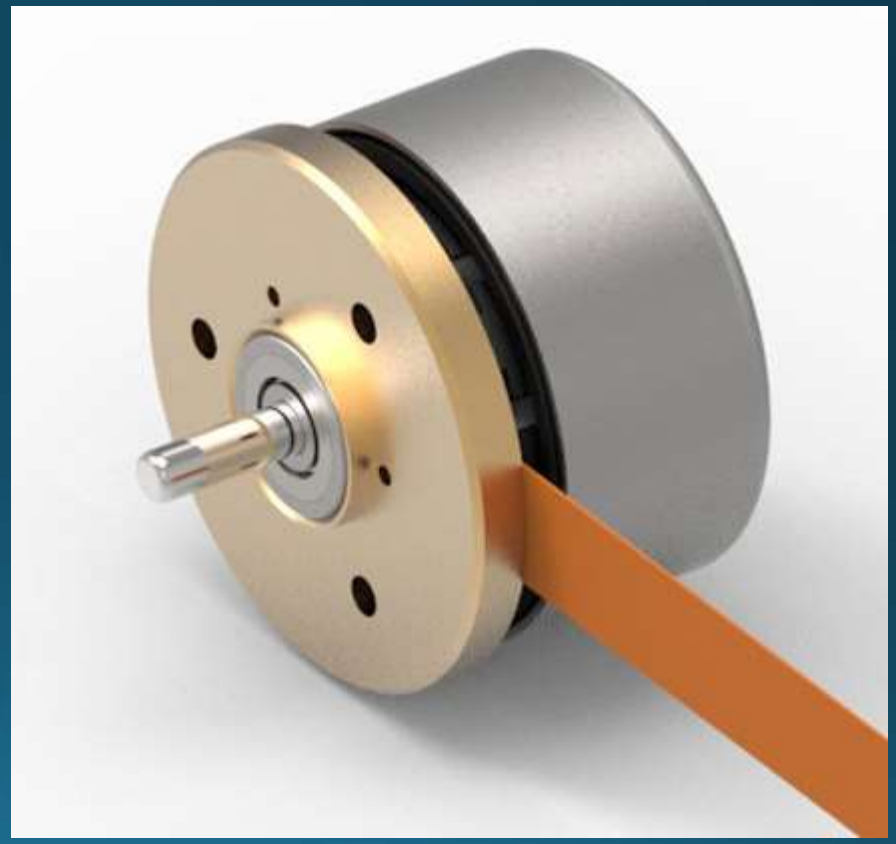


Design Solution – MockSat Motor

- Using current I_{ms} and inputting this into the Simulink with a step command of 75°
- Gives a $23\ mNm$ torque (τ_{ms}) needed by the Mocksat (ms) to meet bandwidth response requirements of our system
- Then using I_{rw} , and τ_{ms}, α_{rw} is calculated
- Integrate acceleration over the time the torque is applied which gives ω_{rw}
- $\omega_{rw} = 206\ rpm$

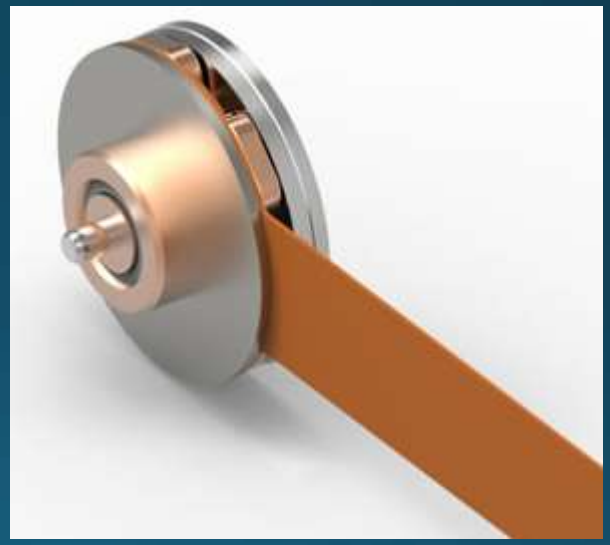
Attitude Control: Motors

- Maxon Motors USA
- Stronger option
- EC brushless
- 6, 9, 12, 24V
- 5W
- 2-5 mNm or 5-10 mNm rated
- Price: 80-220 USD
- 200 N static axial shaft load
- Hall sensors for speed control



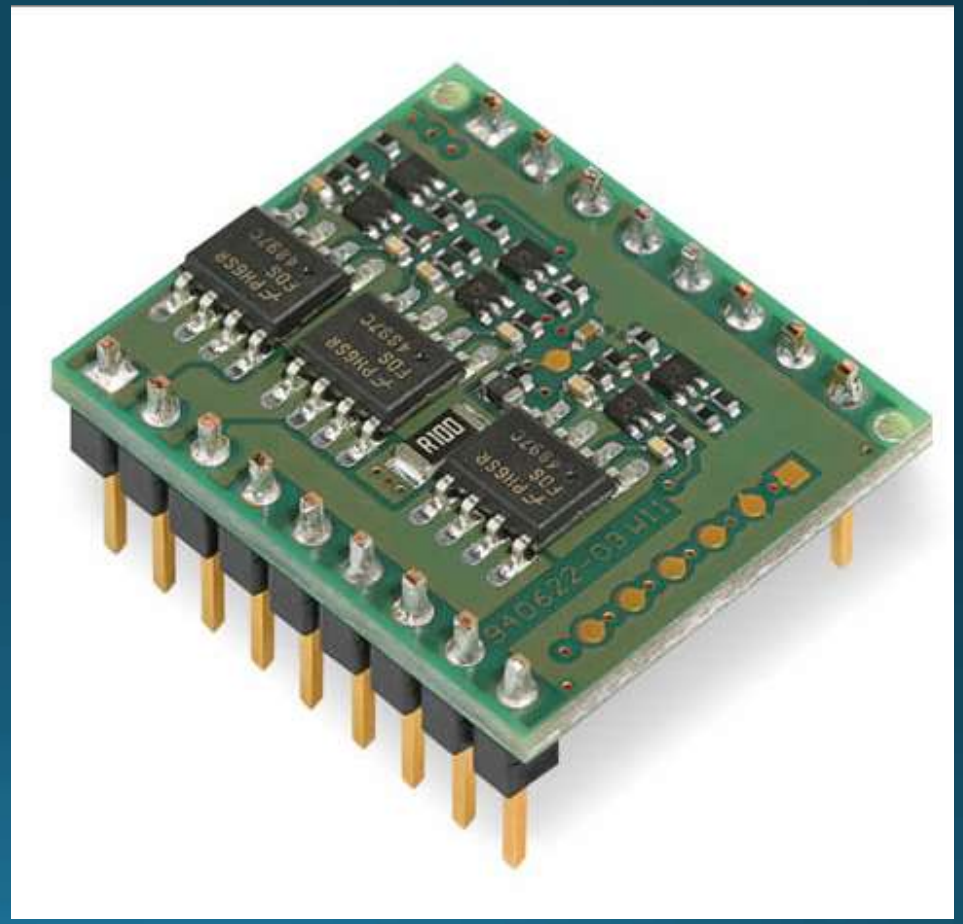
Attitude Control: Motors

- Maxon Motors USA
- Finer attitude control
- EC brushless
- 4V
- 0.2W
- .25 mNm rated
- Price: 200 USD
- 20 N static axial shaft load
- Hall sensors for speed control



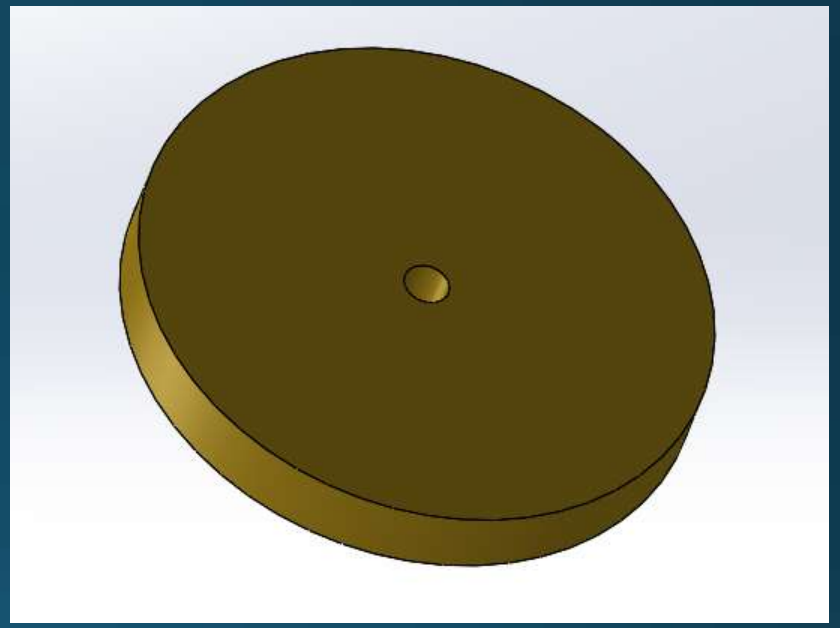
Attitude Control: Motor Controller

- Maxon Motors USA
- EC motors up to 48W
- Hall sensor (EC motor)
- Open & closed loop control
- 46.8 KHz PWM clock
- 5mV resolution
- 8-24 V operating voltage
- Price point: 50 USD



Design Solution – MockSat Reaction Wheels

- Material: Brass
- Mass: $0.974\ lbm$
- Radius: $2\ inches$
- Moment of Inertia: $0.0135\ lbm - ft^2$

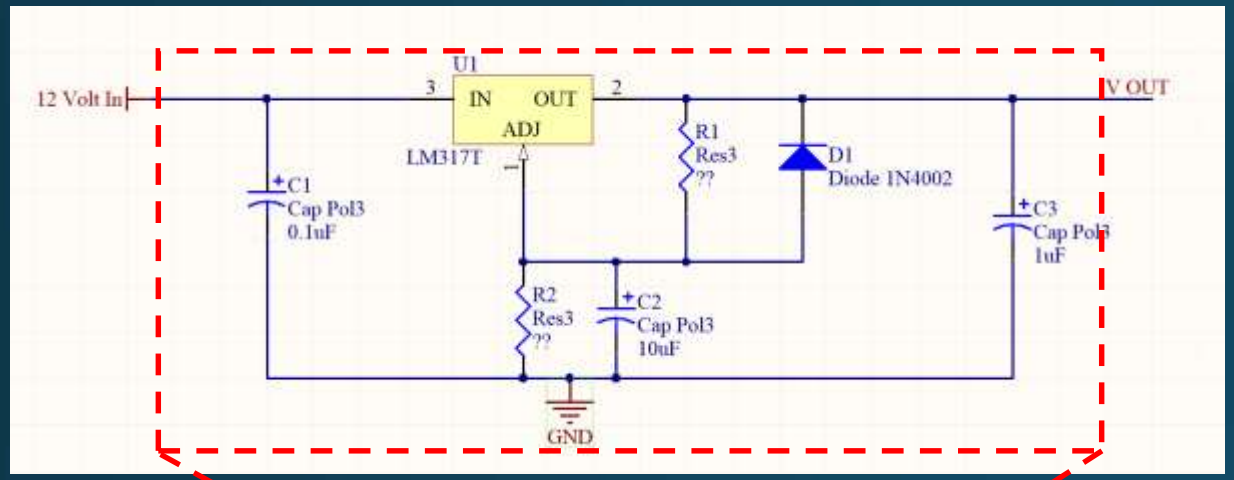


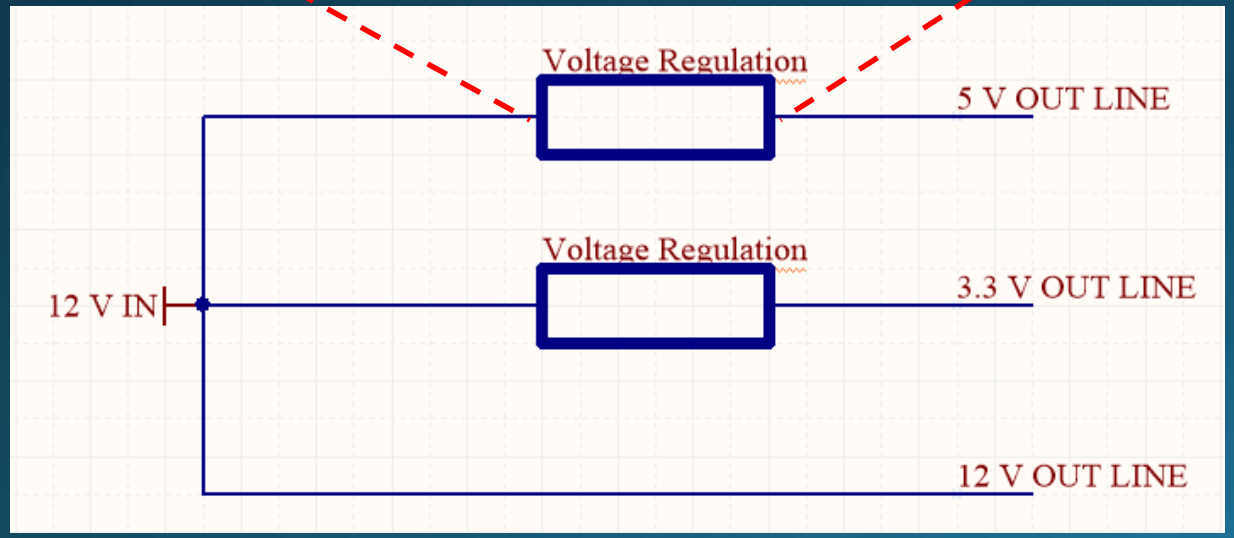
Design Requirements and Satisfaction – MockSat EPS Comparisons

Circuit Type	Total Power Draw (W)	Total Current Draw (A)
LM317	16.98	1.42
DC-DC Conv.	10.31	0.86

- Using DC-DC converters is more efficient. All of the converters found have efficiencies between 70-90 percent, where LM317 efficiency depends on the load properties, and can be as low as 25-50 percent.
  - This affects battery selection, as well as heat sink considerations
- Initially believed we would use analog sensors, which would require less noise in the power circuit. This is no longer a concern as we are using all digital sensors.
- Noise levels of each circuit are on the same order: LM317 circuit uses multiple capacitors to reduce peak to peak noise in voltage, DC-DC converter circuit uses an inductor and capacitor to reduce noise.

Design Solution – MockSat EPS (Voltage Regulator)

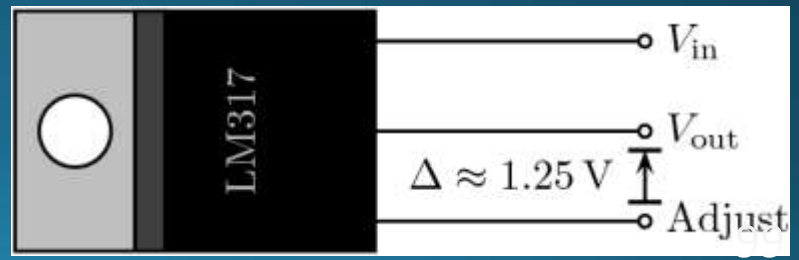




- Purpose: To take unregulated 12 V from a battery and regulate it to clean 8V, 3.3V, and 6V lines
- Uses the LM317 voltage regulator
- Can set output voltage using two resistors

$$V_{out} = V_{ref}\left(1 + \frac{R_2}{R_1}\right) + (I_{adj} * R_2)$$

- Reference and Adjust properties are set by LM317:
  - V_ref = 1.25 V
  - I_adj = 50 uA
- Added capacitors to reduce ripple on output
- LM317 pinout:



Design Requirements and Satisfaction – MockSat EPS (Voltage Regulator)

- 3.3 V Line
  - Powers the MPU 6000 IMU, the Atmel MCU, and the Xbee Communication System
  - Use R1 = 1420 Ohms and R2 = 2200 Ohms to achieve output of 3.3 V
- 6 V Line
  - Powers the motors for the two reaction wheels
  - Use R1 = xxx and R2 = xxx to achieve output of 6 V
- 8 V Line
  - Powers all three of the PIXY cameras
  - Use R1 = 420 Ohms and R2 = 2200 Ohms to achieve output of 8 V

Design Requirements and Satisfaction – MockSat EPS (Voltage Regulator)

- Power budget using a voltage regulator

MockSat Power Budget (Using LM317 Voltage Regulator)					
Component	**Voltage Rating (V)**	**Current Draw (A)**	**Power Draw (W)**	**Power Draw From Battery (W)**	**Efficiency of Voltage Regulation**
Motor	12	0.125	1.5	1.5	1.000
Micro-Controller (Atmel SAM E70)	5	0.5	2.5	6	0.417
Xbee Comm System	3.3	0.12	0.396	1.44	0.275
Pixy Camera (3)	8	0.14	1.12	1.68	0.667
MPU 6000 IMU	5	0.25	1.25	3	0.417
Total				16.98	

- Total power draw calculated results in a total current draw of ~2.3 A if using a 12 V battery
- Efficiencies are found from datasheets, and used to calculate the power drawn from the battery for each component.
  - Note: motor efficiency is 100% because we won't need to regulate voltage from 12 V battery to 12 V component

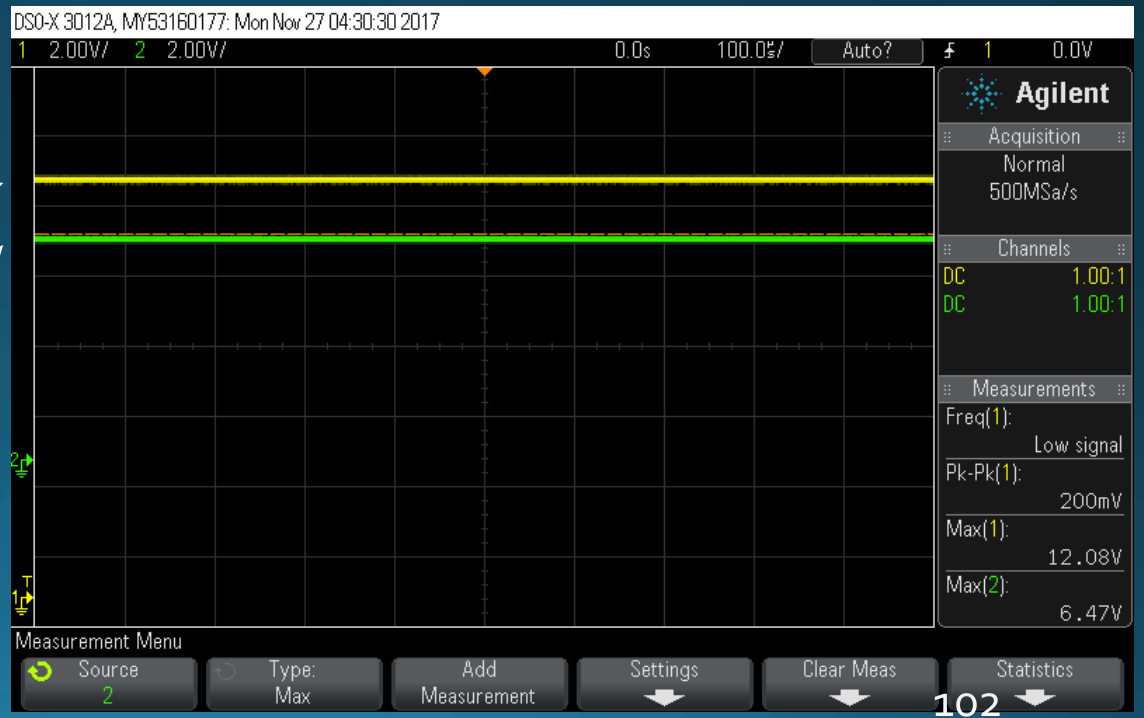
Design Requirements and Satisfaction – MockSat EPS (Voltage Regulator)

- Verification and Validation – Output Voltage

- R1 = 992 Ohms
- R2 = 3860.7 Ohms
- V_out_nom = 6.31 V

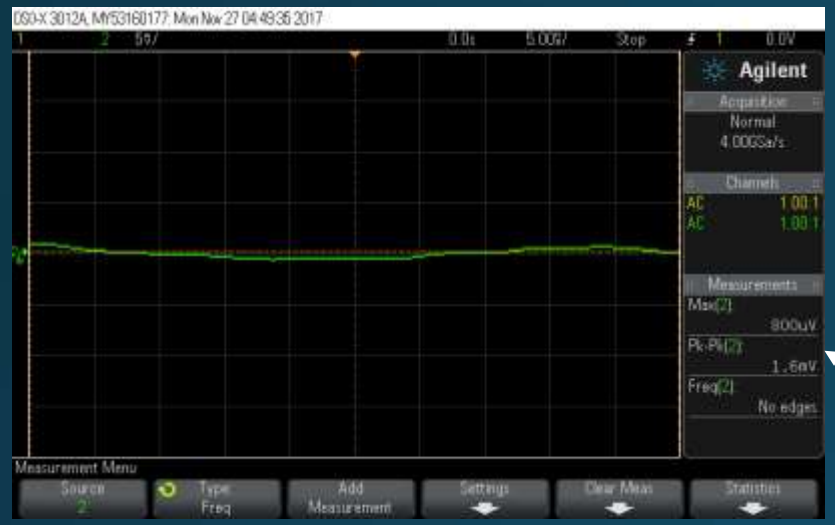
V_in

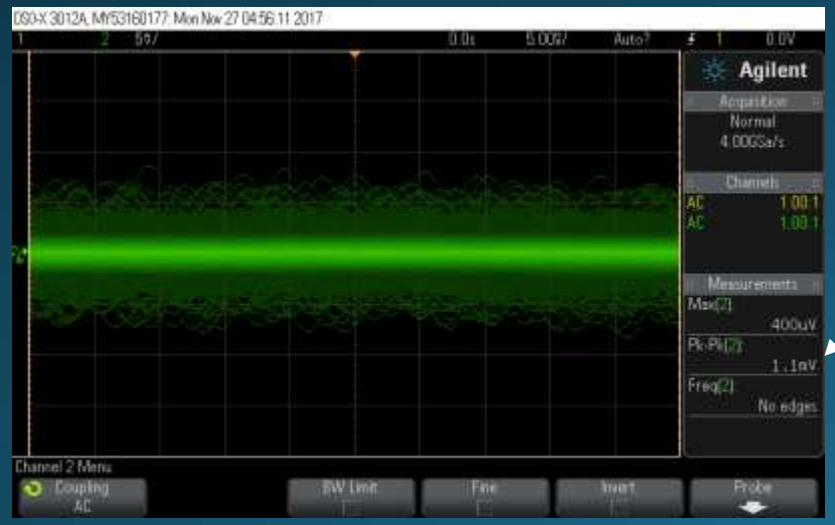
V_out



Design Requirements and Satisfaction – MockSat EPS (Voltage Regulator)

- Verification and Validation – Noise Reduction

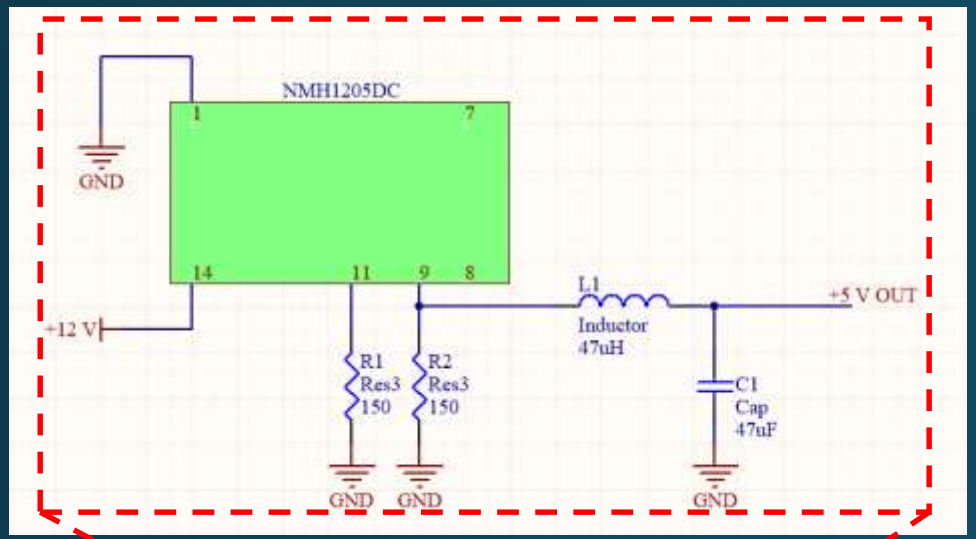


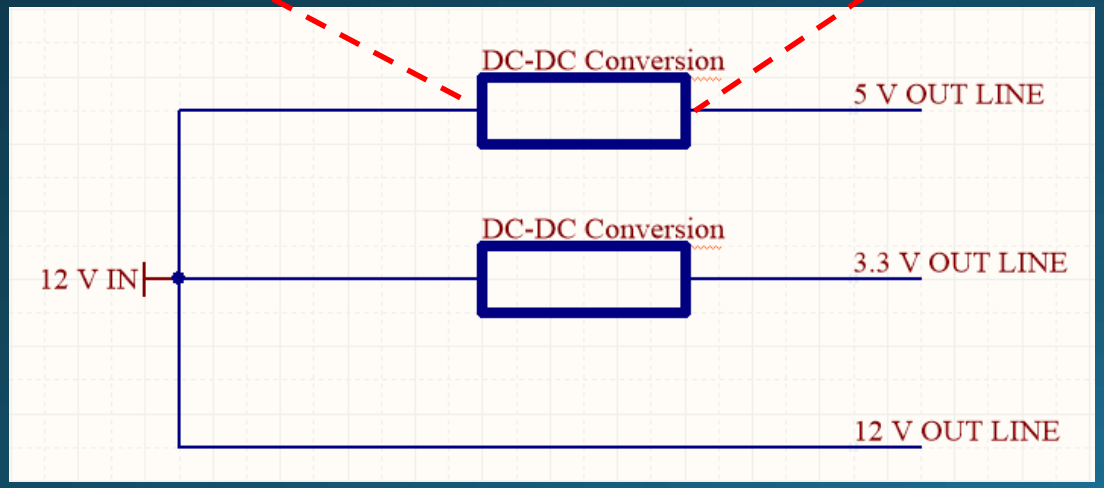


Peak to Peak voltages (AC Coupling)

- Seeing peak to peak voltages on circuit output of between 1-3 mV
- Verified that circuit both lowers the voltage to a desired value, as well as reduces noise on the output.

Design Solution – MockSat EPS: DC-DC Converter





- 3.3 V Line
  - To Xbee Transciever
  - Nominal current up to 606 mA.
  - Efficiency of 73%
- 5 V Line
  - To MCU, Pixy Came
  - Nominal current up to 400 mA.
  - Efficiency of 78%
- 24 V Line
  - To motors
  - Nominal current up to 3 A.
  - Efficiency of 89.5%

Design Solution – MockSat EPS (DC-DC Converter)

- Power budget using DC-DC converters and 12 W Motor

MockSat Power Budget (Using Murata DC-DC Converter)					
Component	**Voltage Rating (V)**	**Current Draw (A)**	**Power Draw (W)**	**Power Draw From Battery (W)**	**Efficiency of Voltage Regulation**
Motor	24	0.5	12	20.24	0.593
Micro-Controller (Atmel SAM E70)	5	0.4	2	2.56	0.780
Xbee Comm System	3.3	0.12	0.396	0.54	0.730
Pixy Camera (3)	5	0.14	0.7	0.90	0.780
MPU 6000 IMU	5	0.25	1.25	1.60	0.780
Total				27.64	

- Total power draw calculated results in a total current draw of ~2.3 A if using a 12 V battery
- Efficiencies are found from datasheets, and used to calculate the power drawn from the battery for each component
  - Note: motor efficiency incorporates efficiency of DC-DC converter (89.5%), motor controller (92%), and the motor (79%)

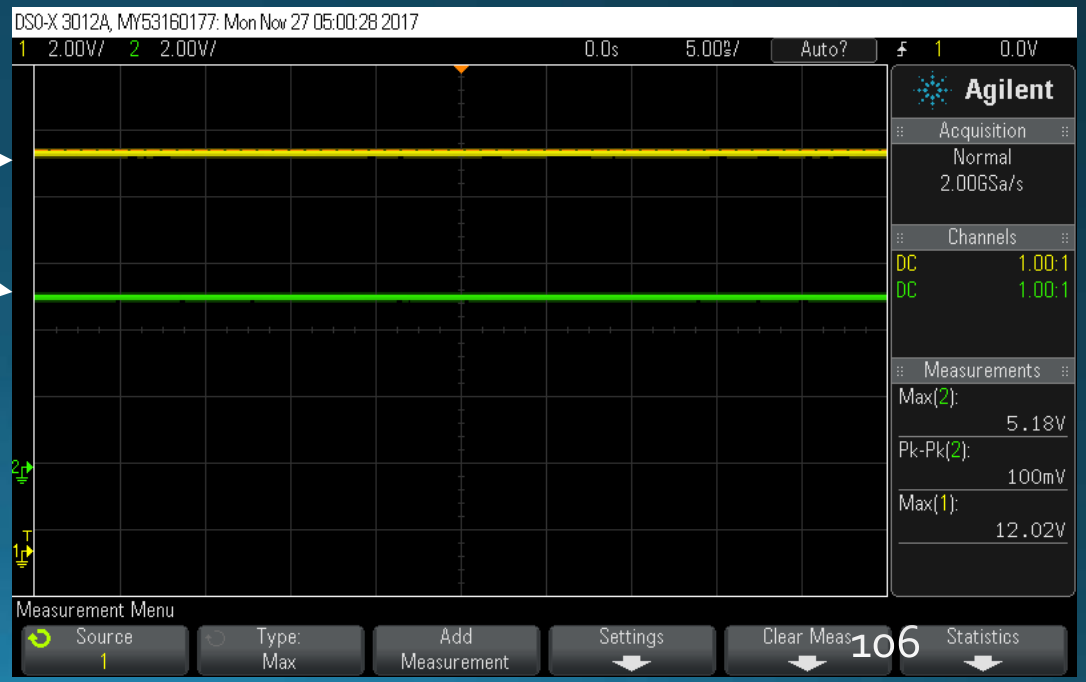
V&V – MockSat EPS (DC-DC Converter)

- DC-DC Conversion

- Nominal input voltage of 12 V and output voltage of 5 V for this converter

V_in

V_out

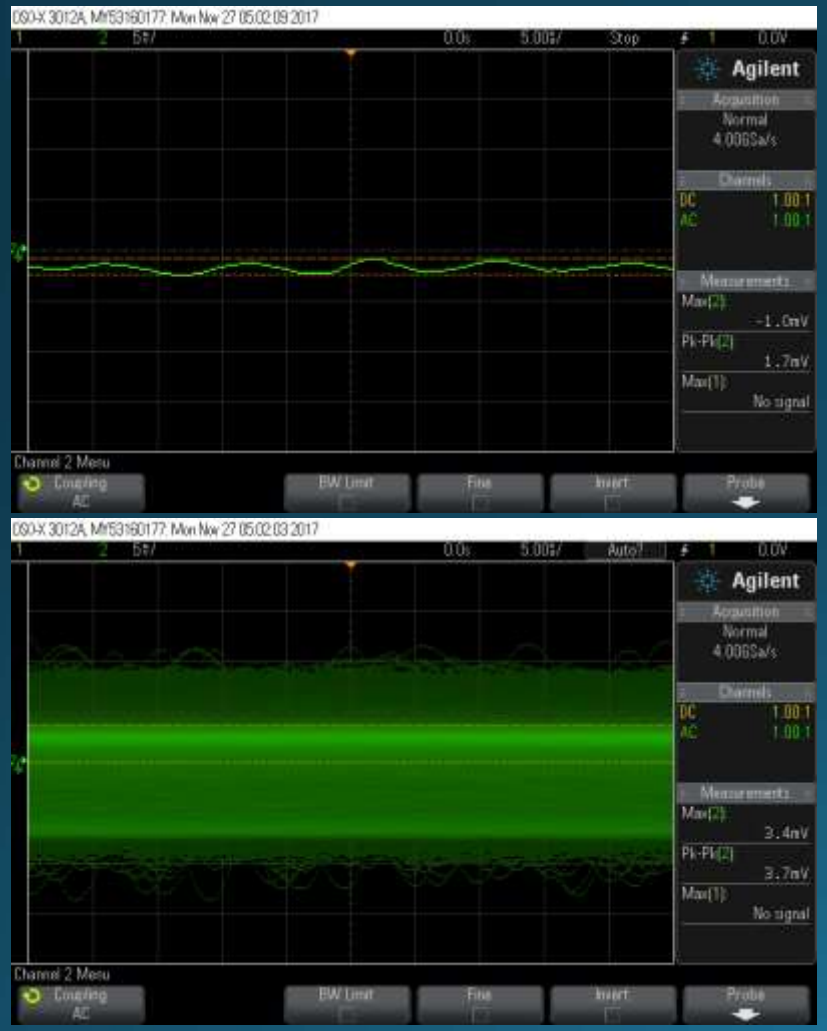


Design Requirements and Satisfaction – MockSat EPS (DC-DC Converter)

- 3.3 V Line
  - Can use Murata PS MEJ2S1203SC converter
    - Nominal output of 3.3 V, current up to 606 mA
    - Efficiency of 73%
- 5 V Line
  - Can use Murata PS NMH1205DC converter
    - Nominal output of 5 V, current up to 200 mA
    - Efficiency of 80%
- 24 V Line
  - Can use Murata PS UWE-24/3-Q12 converter
  - Nominal output of 24 V, current up to 3 A
  - Efficiency of 89.5%

V&V – MockSat EPS (DC-DC Converter)

- Noise Reduction



Peak to Peak voltages (AC Coupling)

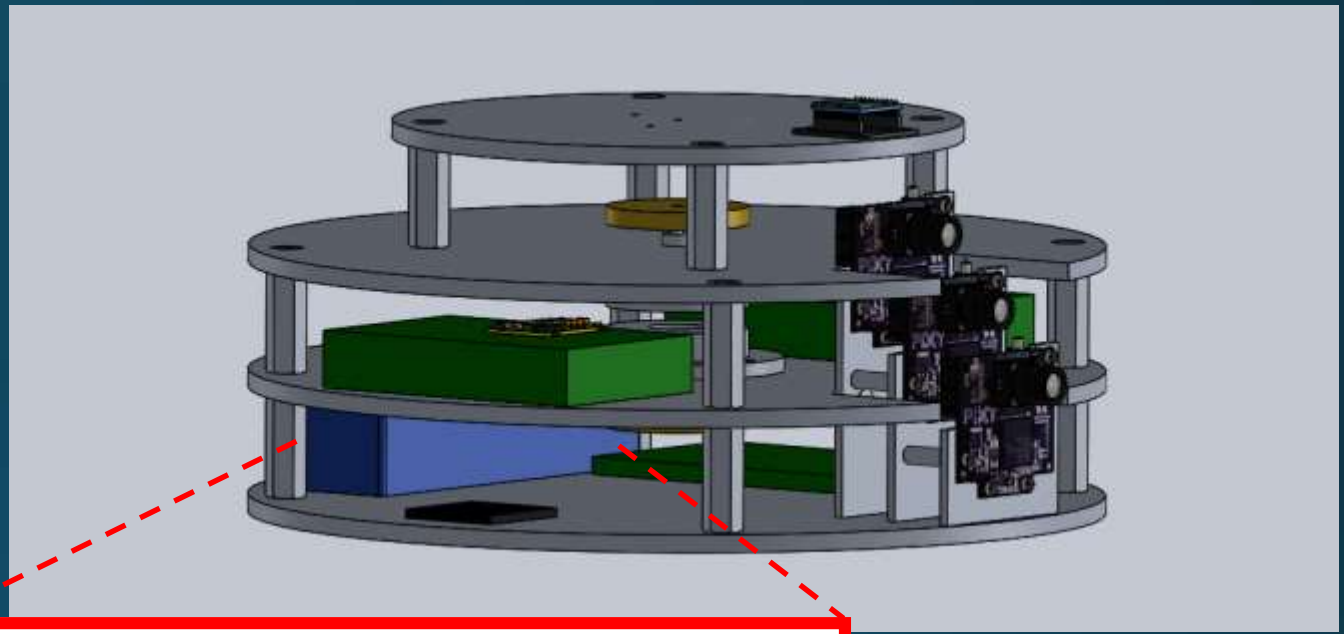
- Seeing peak to peak voltages on circuit output of between 1-5 mV
- Verified that circuit reduces noise on the output
  - Important for use of analog devices on MockSat

Design Solution – MockSat EPS: Battery Selection

- Add in 50% factor of safety, assume 60% usable battery capacity

$$\frac{0.86\ Ah + 50\%}{60\%} = 2.15\ Ah$$

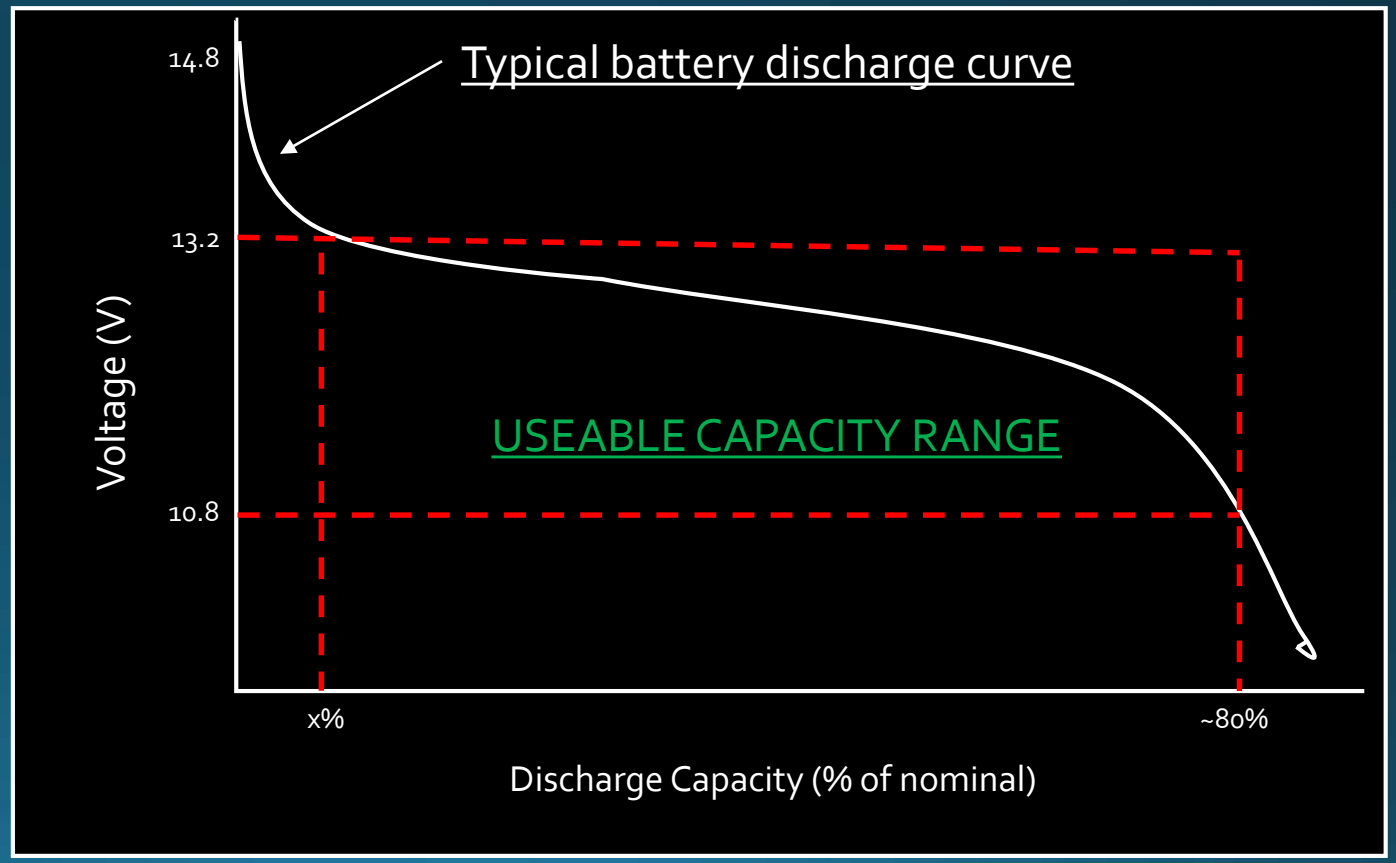
- Turnigy 5000 mAh 4S 40C LiPo battery
  - Provides 40C*5 Ah= 200 A maximum continuous discharge



V&V– MockSat EPS (Battery)

- Using a 14.8 V rated LiPo battery
  - Find the battery capacity at which the voltage measures 13.2 V
  - Only discharge the battery to ~80% of its nominal capacity for safety
- Will test the battery once it is acquired to define actual range of usable capacity
  - Discharge the battery at loads representative of our system and measure voltage drop over time

$$\frac{0.86\ Ah + 50\%}{(80 - x)\%} = Capacity$$



Attitude Control: Sensors

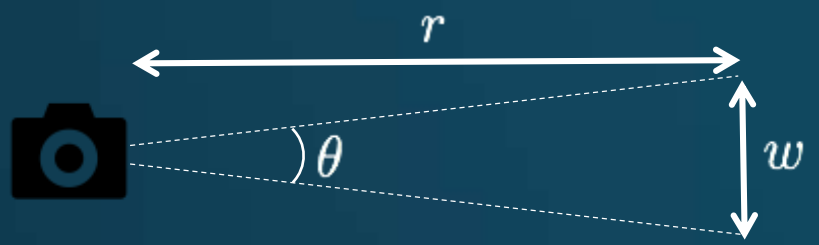
Nomenclature

X_t Target Variable

X_f Fine Sensor Variable

X_c Coarse Sensor Variable

Pointing Windows:



$$w = 2r \tan\left(\frac{\theta}{2}\right)$$

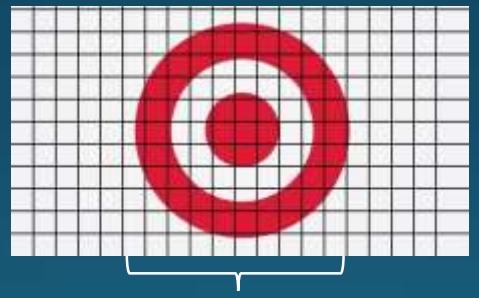
$$L \equiv \frac{meters}{pixel}$$

$$w_t \in [0.0266, 0.0509]\ m$$

$$w_f \in [0.0533, 0.2587]\ m$$

$$w_c \in [0.2219, 0.8953]\ m$$

Assume at least 10 pixels across target window



Minimum meter per pixel ratio

$$L_{min} = 0.0027\ \frac{m}{pix}$$

Target Size:

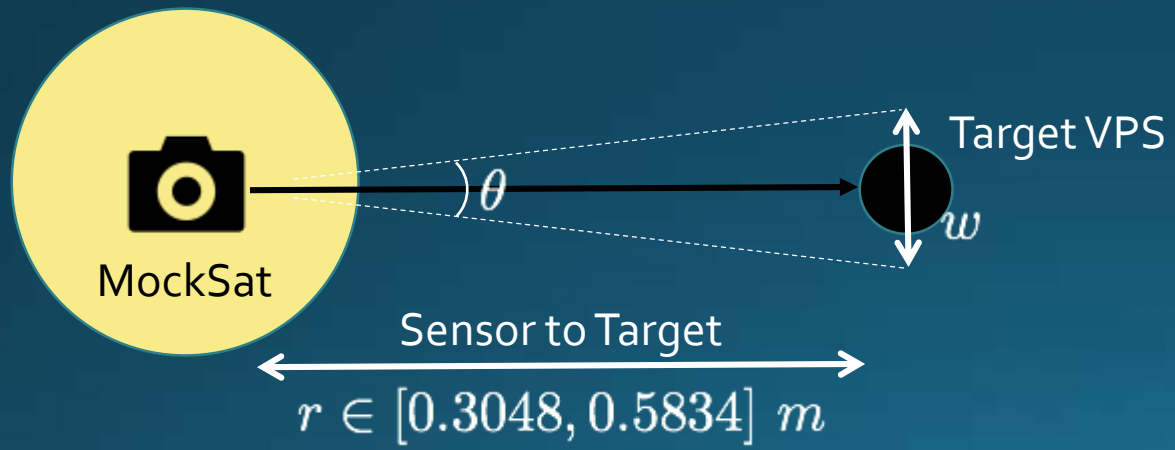
$$d \in [0.0027, 0.0533]\ m$$

CPE – Fault Injection and Management System: Sensors

Fine Attitude Sensor Field of View $[10^o, 25^o]$

$$w = 2r \tan\left(\frac{\theta}{2}\right)$$

$$L \equiv \frac{meters}{pixel}$$



With 640 pixels wide and θ = 21°:

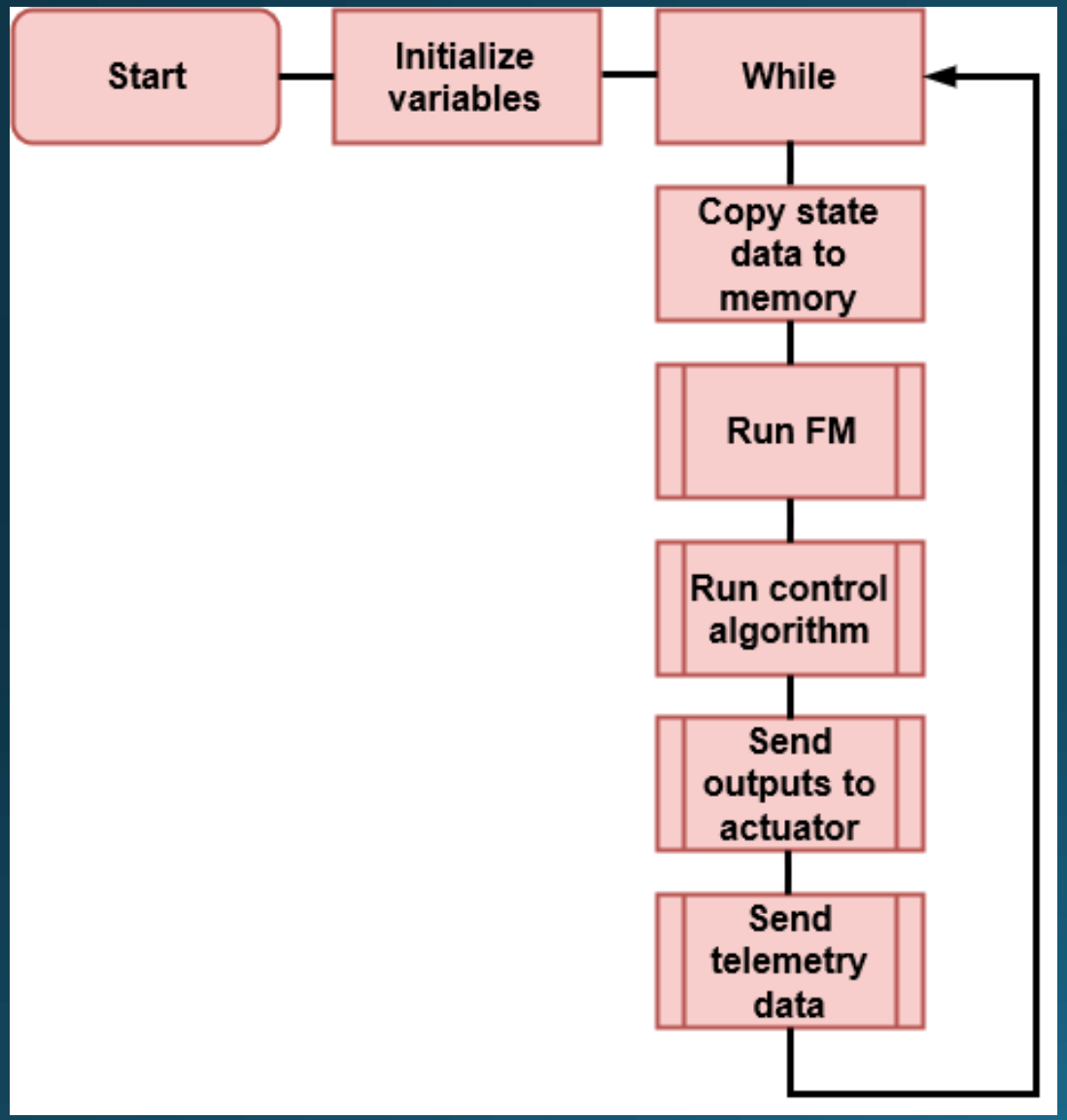
We would need 178 pixels to view a standard light bulb with a width of 60 mm.

Attitude Control: Sensors -Pixy Specs

Pixy CMUcam5

- 204 dual core MHz Processer
- UART serial, SPI, I2C, USB Buses
- Digital and Analog Output
- 640x480 8-bit grayscale at 50 FPS

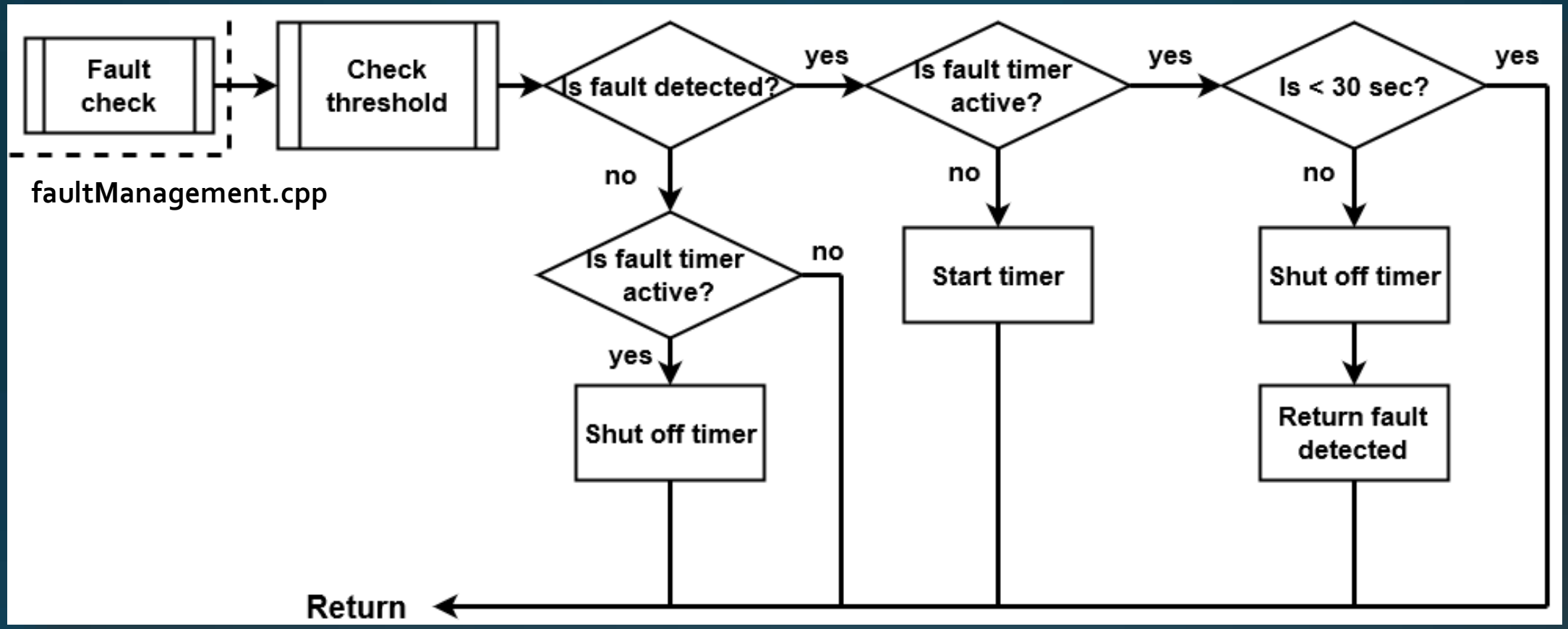
Software: Main Loop



Main.cpp logic flowchart

- Main loop for software operation, runs indefinitely
- Copy current state from all sensors at the beginning of each iteration to ensure data consistency across a loop iteration

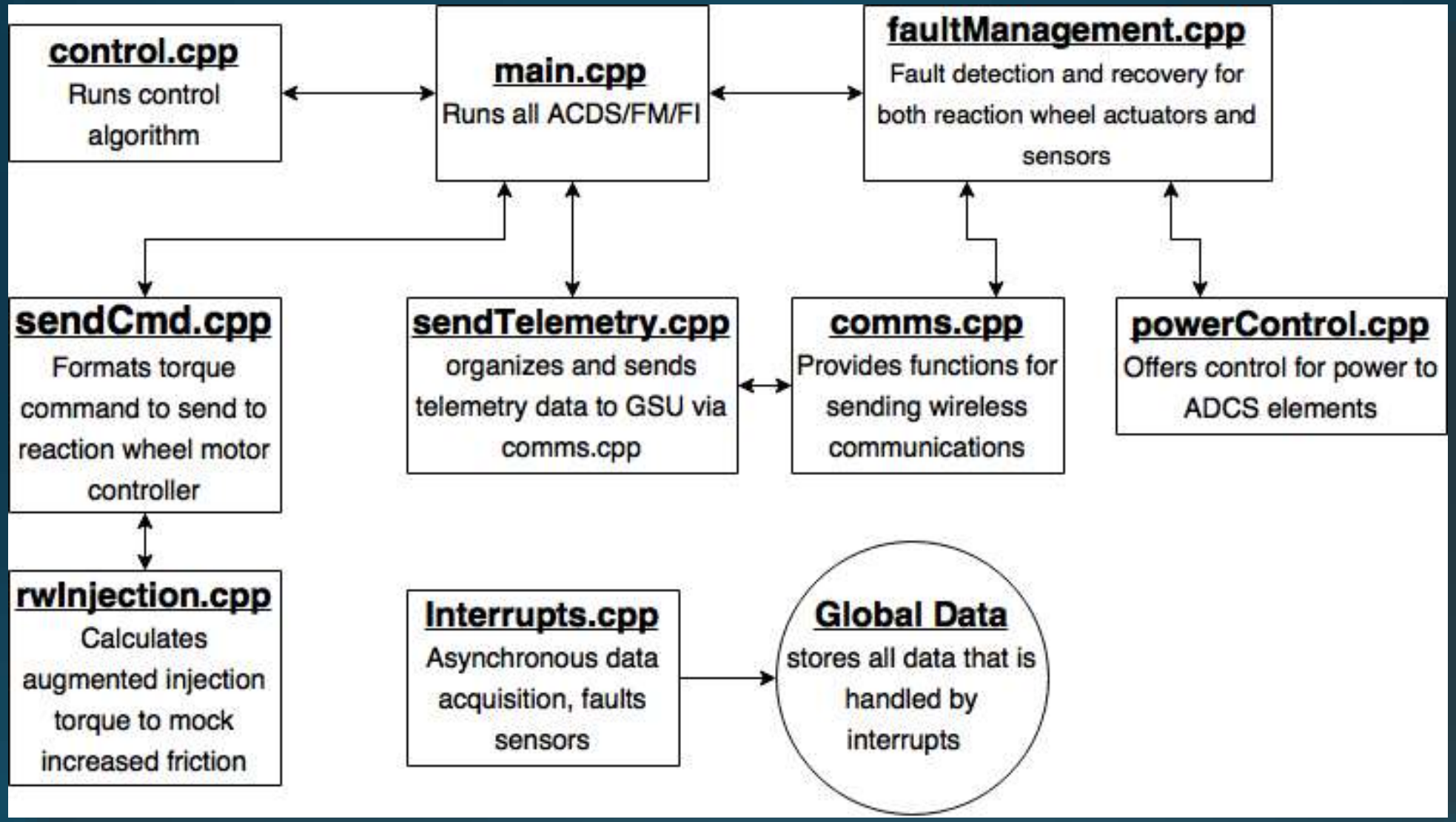
Design Requirements and Satisfaction – Fault Management



Fault checking algorithm flowchart

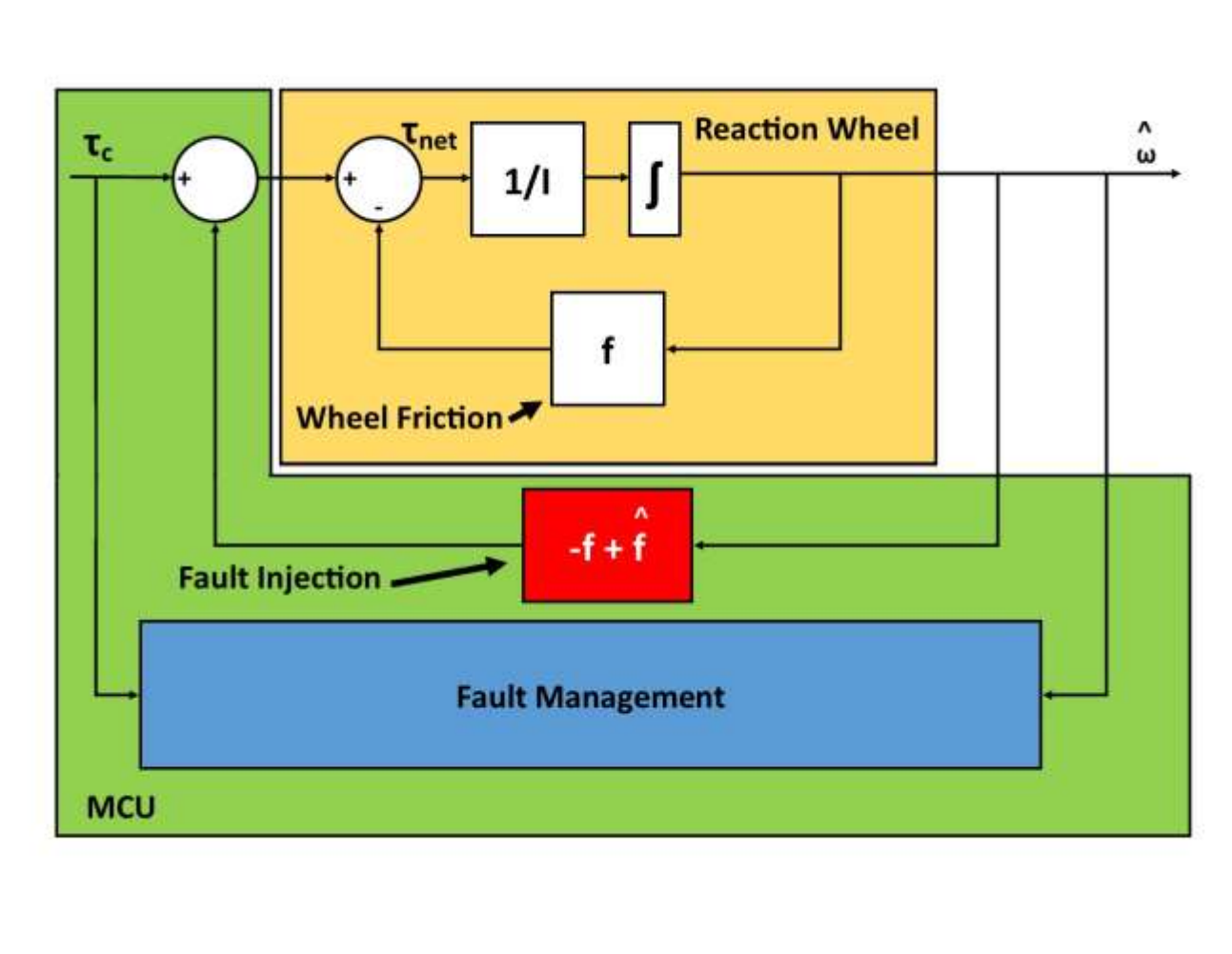
- Only detect persistent faults
- Use same detection method for RW and fine sensor
- This allows for code re-use, ideally to other systems

Design Solution – Software: Class Diagram



Class diagram showing major classes/programs, their functions, and their interactions with other software modules

Fault Injection: Reaction Wheel Friction



FBD for induced reaction wheel friction

- Friction is a common and near inevitable fault in the reaction wheels of space systems
- Fault injection system creates apparent friction in software only
  - This DOES NOT *physically* increase the friction in the reaction wheel, but rather it makes the fault management ADCS systems "see" increased friction
- Injects fault into reaction wheel by:
  - Subtracting off nominal friction
  - Adding induced friction function
- Nominal Friction function:

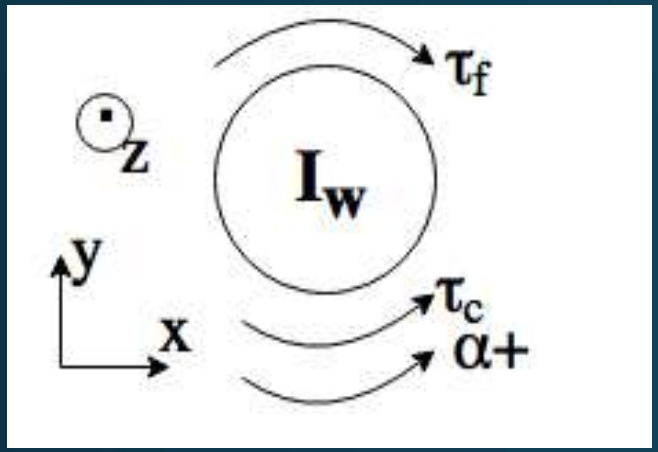
$$\tau_f = f(\omega)$$

- Induced friction function:

$$\hat{\tau}_f = \hat{f}(\omega)$$

Fault Management: Reaction Wheel Friction

Model:



Reaction wheel dynamics

- Governing Equation:

$$\sum \tau = I\alpha \text{ (1-DOF)}$$

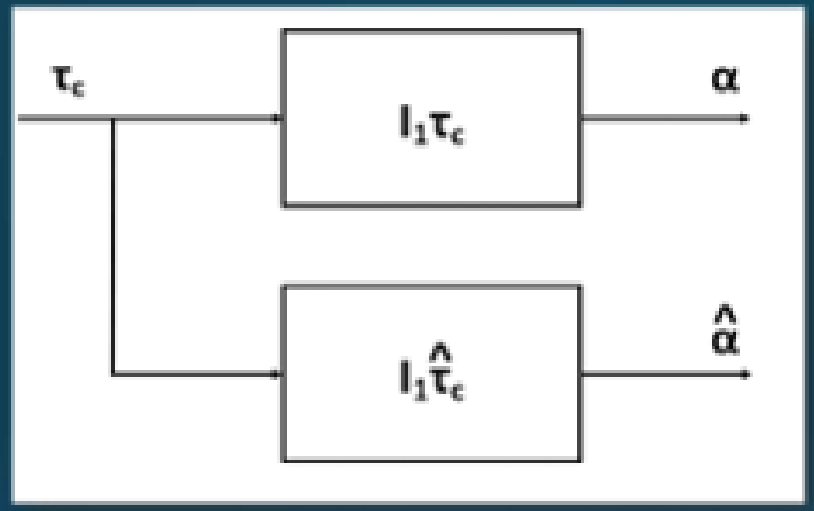
- Nominal friction:

$$\tau_c - \tau_f = I\alpha$$

- Induced Friction:

$$\tau_c - \hat{\tau}_f = I\hat{\alpha}$$

Detection:



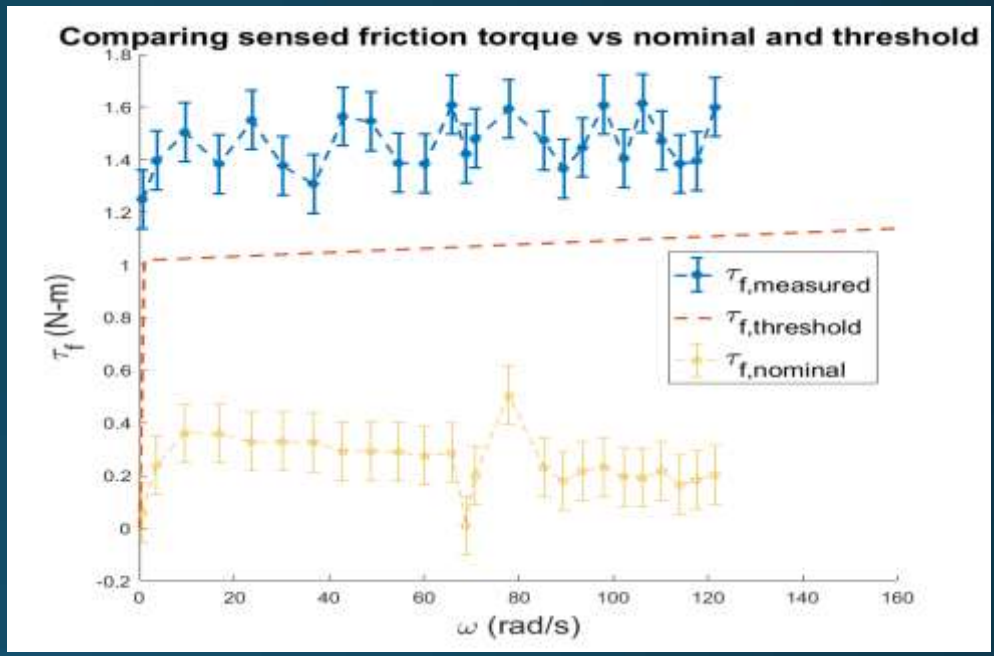
Comparison between model and actual

- Fault Management Process:
  1) Read output wheel speed
  2) Calculate induced friction from governing equation

$$\hat{\tau}_f = I\hat{\alpha} - \tau_c$$

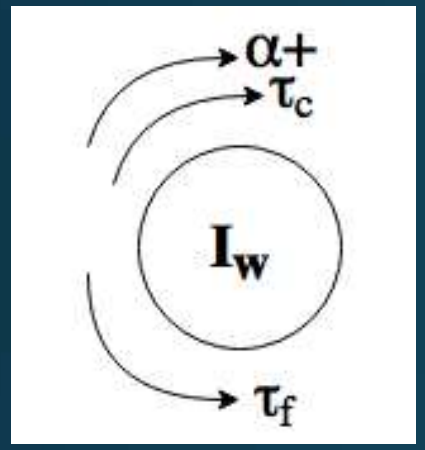
  3) Compare vs model. If friction is above threshold value, then fault exists in system

Feasibility Example:



- ASEN 3200 spin module data used to create nominal friction function
- Induced friction function used to inject fault
- Modeled using governing equation and Matlab's ode45 solver
- Friction in system is greater than threshold value, therefore this is feasible

CPE – Fault Injection and Management System: Actuators



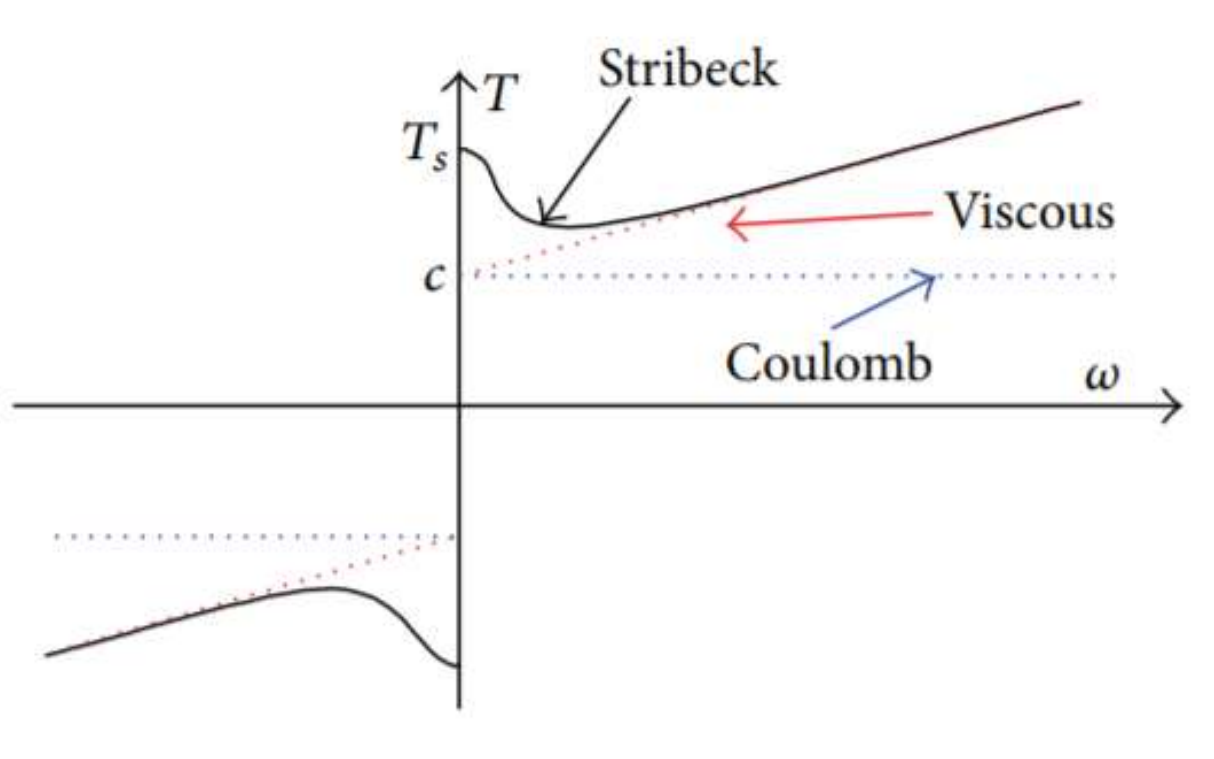
Reaction wheel dynamics

τ_{net} = Net torque on reaction wheel
τ_c = Commanded torque
τ_f = Torque due to friction, nominal
I_ω = Reaction wheel moment of inertia
α_ω = Reaction wheel angular acceleration

$$\tau_{net} = \tau_c - \tau_f = I_\omega \alpha_\omega$$

$$\tau_f = f(\omega)$$

CPE – Fault Injection and Management System: Characterizing Reaction Wheel Friction



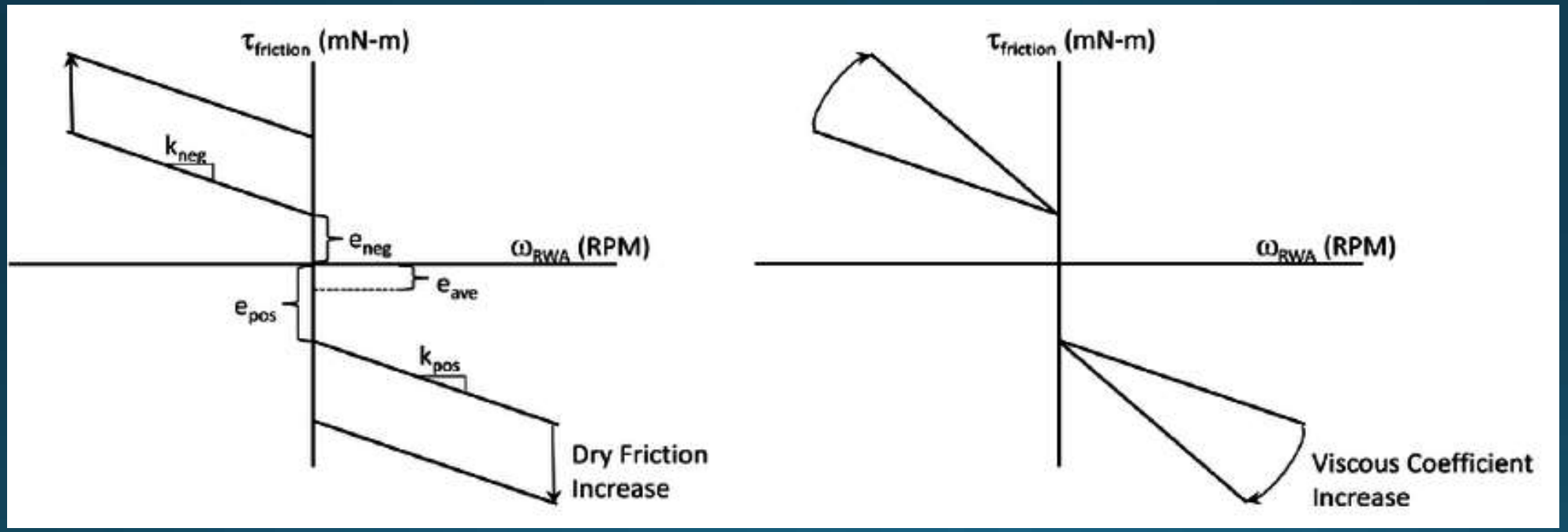
Representative friction torque curve of reaction wheel

- Friction in reaction wheels is combination of Viscous, Coulomb, with some initial Stribeck friction near angular velocities of zero

Source: Carrara, Vlademir, and Hélio Koiti Kuga. "Estimating Friction Parameters in Reaction Wheels for Attitude Control." *Mathematical Problems in Engineering*, vol. 2013, 12 May 2013.

CPE – Fault Injection and Management System: Reaction Wheel Friction Failure

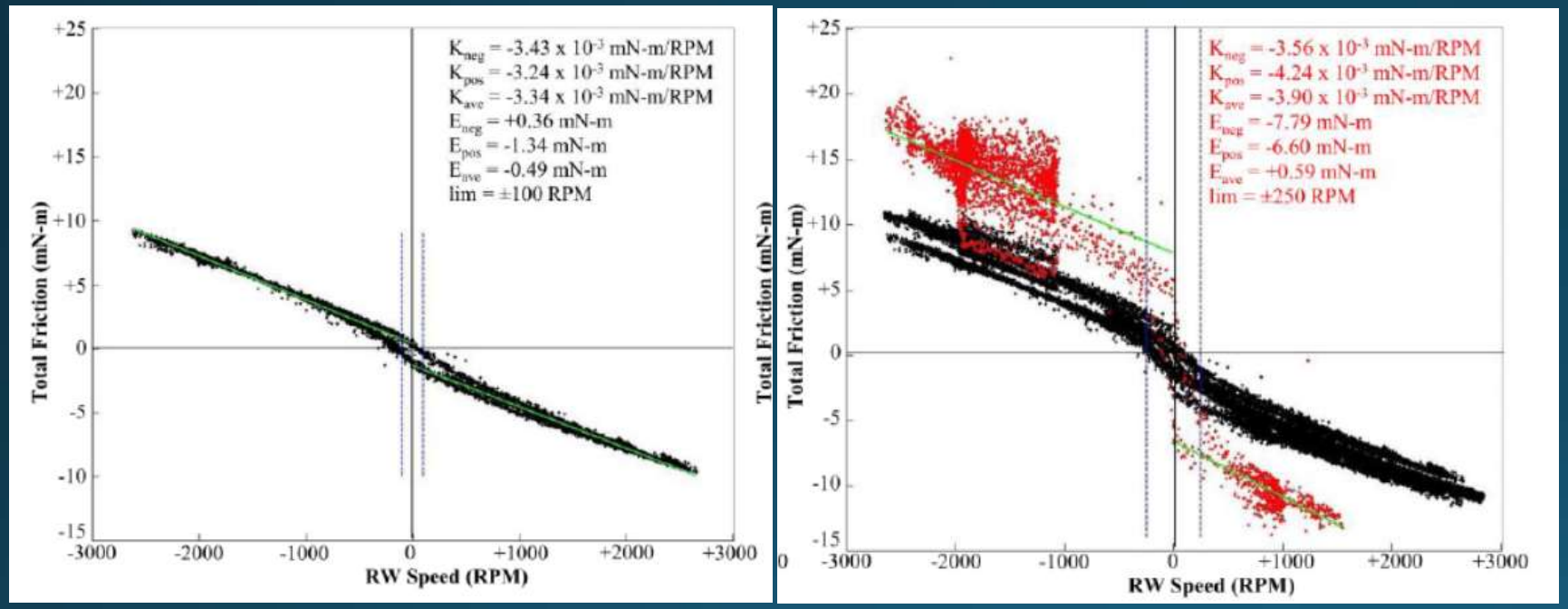
- Hard failures in reaction wheels are caused by an increase in Coulomb friction.



Left: Increase in Coulomb friction. Right: Increase in Viscous friction

Source: Hacker, Johannes M, et al. *Reaction Wheel Friction Data-Processing Methodology and On-Orbit Experience*. AIAA, Aug. 2014.

CPE – Fault Injection and Management System: Reaction Wheel Friction Failure



- Actual on-orbit data of failing reaction wheel
- Hard failure occurs at 5 mN-m above nominal, with nominal static friction of 0.85 mN-m
- Use this scaling for fault detection threshold in our system.

Left: Nominal Friction Data. Right: Increase in Coulomb friction causing hard failure

Source: Hacker, Johannes M, et al. *Reaction Wheel Friction Data-Processing Methodology and On-Orbit Experience*. AIAA, Aug. 2014.

CPE – Fault Injection and Management System: Actuator Management

- Fault management has access to commanded torque as well as reaction wheel angular velocity at discrete time steps. Calculate angular acceleration of the wheel by:

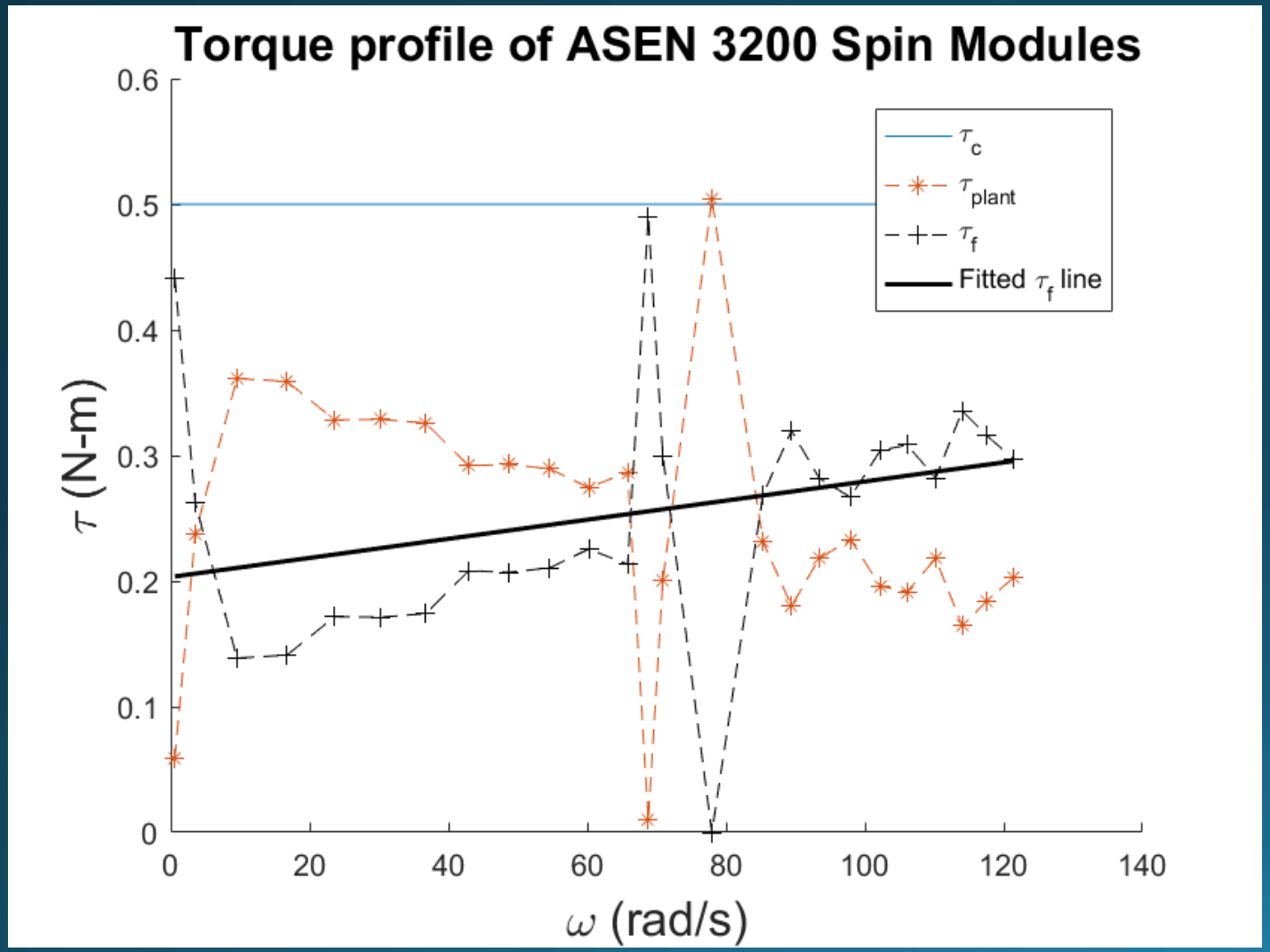
$$\hat{\alpha}_\omega = \frac{\Delta\omega}{\Delta t}$$

- Then, calculate the system friction by:

$$\hat{\tau}_f = \tau_c - I_\omega \hat{\alpha}_\omega$$

- This is then compared versus a threshold friction torque of 4 times the nominal static friction torque present in the reaction wheel.
- If the system friction calculated by fault management is above this threshold value, characterize as a fault

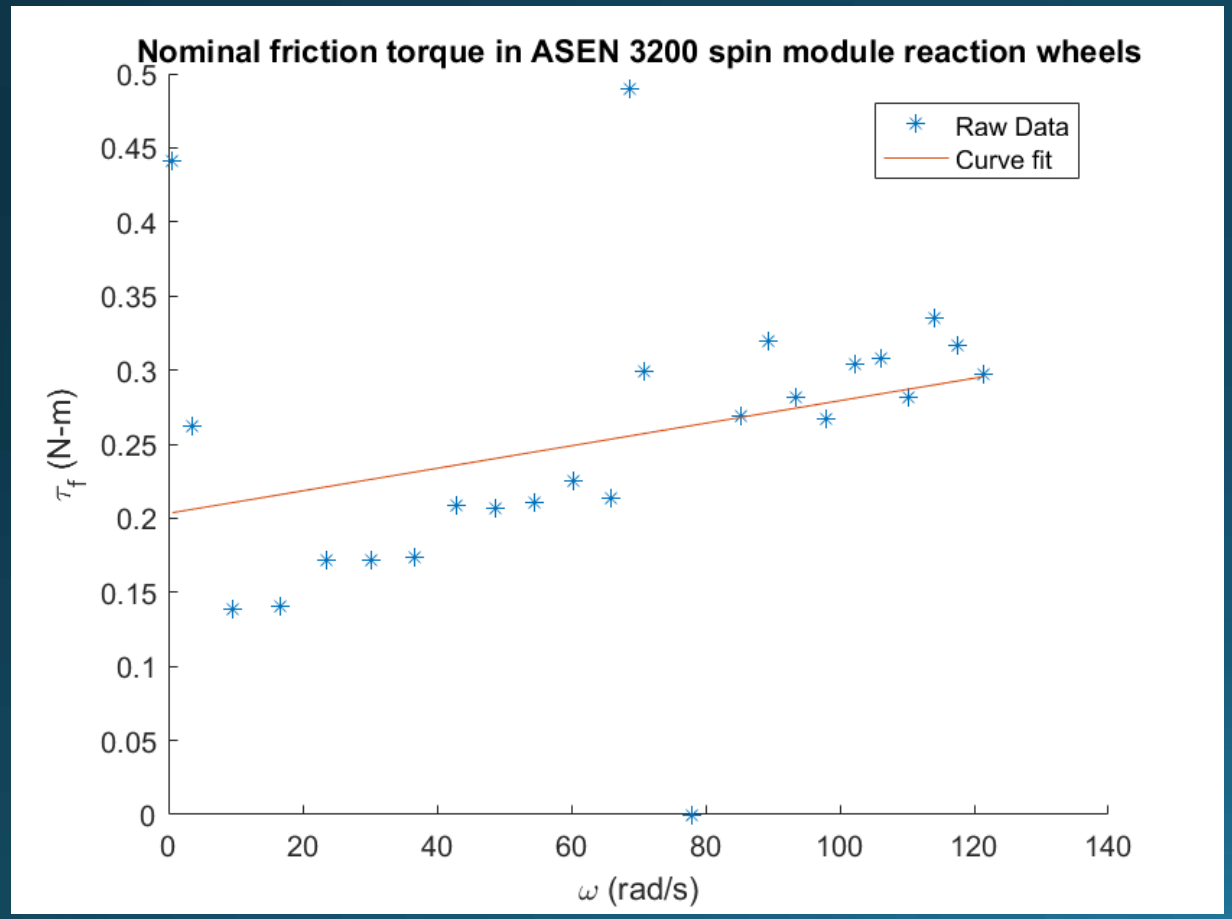
CPE – Fault Injection and Management System: Example Analyzing 3200 Reaction Wheels

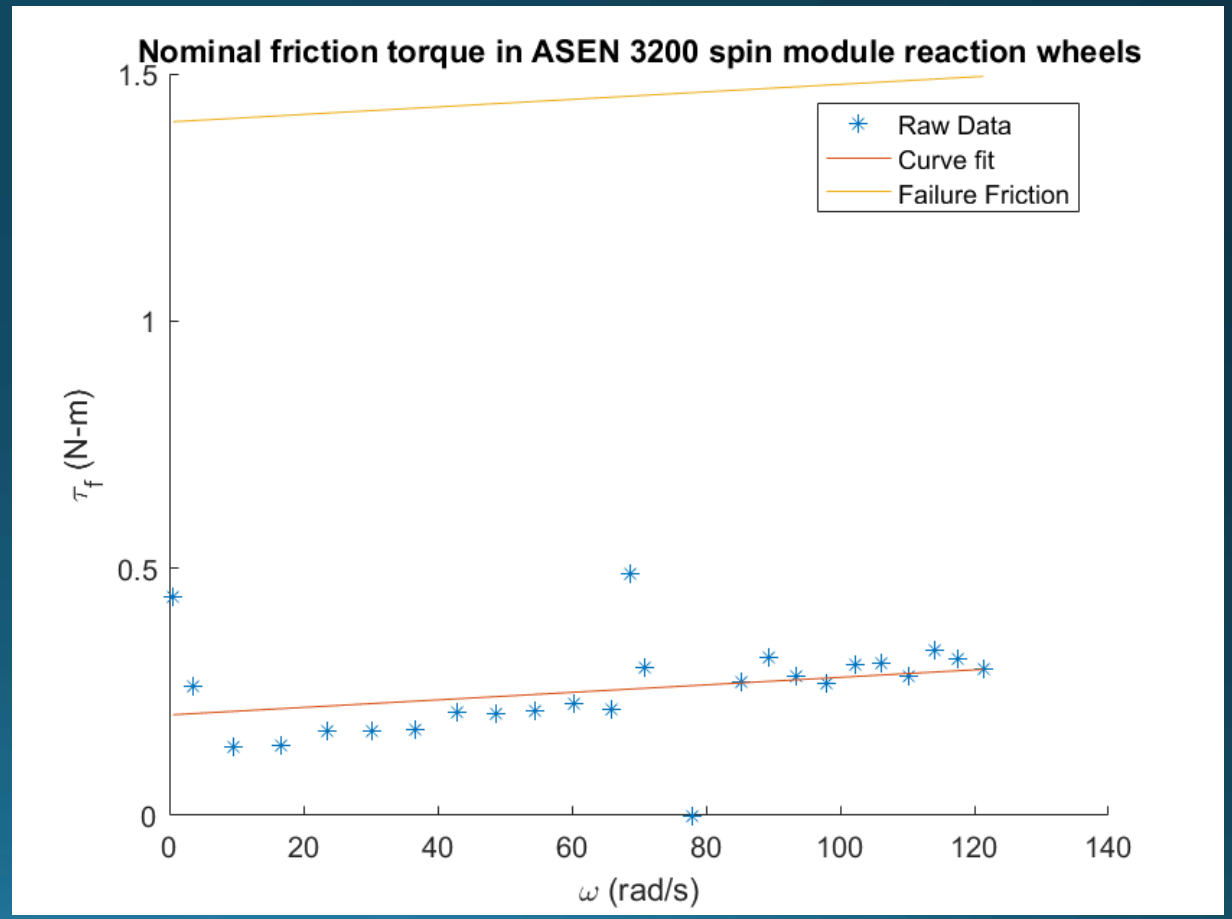


- Used data from ASEN 3200 to examine nominal friction in this system.
- Constant commanded torque of 0.5 N-m
- Data file contained time stamps every 0.1 s with commanded torque and wheel speed.
- From this data, the friction torque present as a function of angular velocity was calcucated.
- Then, a linear fit of this data was made to determine an approximate nominal friction torque as a function of angular velocity.

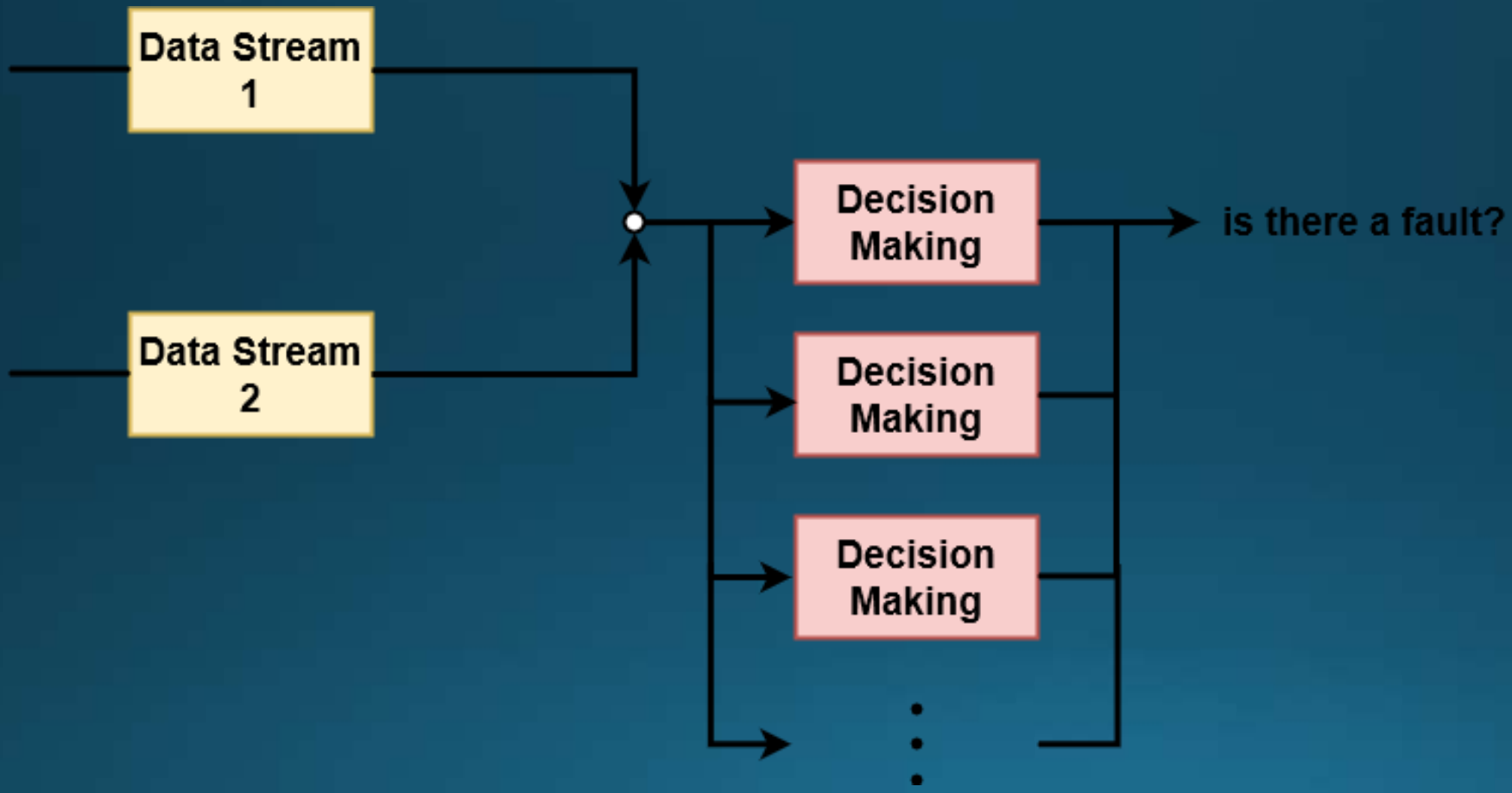
CPE – Fault Injection and Management System: Analyzing 3200 Reaction Wheels

- Triggering a fault – Example using ASEN 3200 Spin Module data



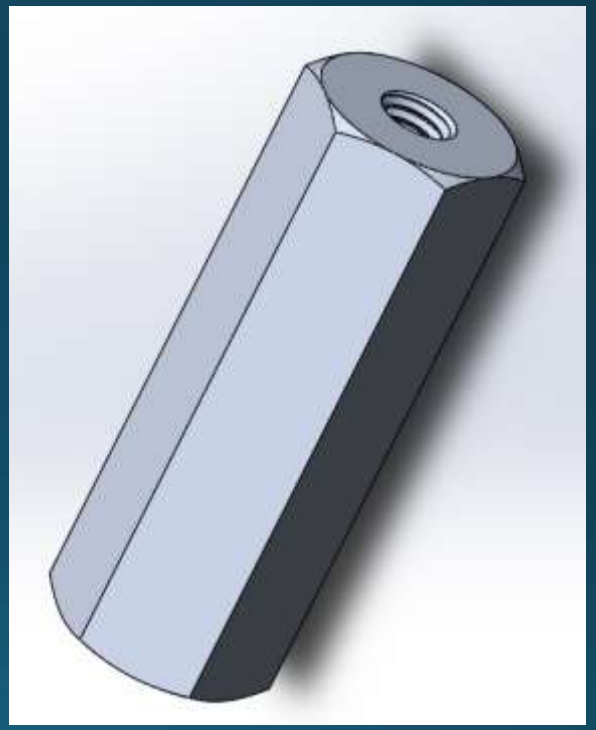


Design Requirements and Satisfaction – Fault Management Interface



Structural Analysis - Standoffs

- Max Load: 9.65 lbs (over 4 standoffs)
- Assumptions: Constant circular cross section
- Max Axial Stress: 1.415 psi
- Material Yield Stress: 40 ksi
- Critical Stress for Buckling: 2467 ksi
- Factor of Safety: 1743 x 10^3
- Change in Axial Length: 2.12 x 10^-3 in



Structural Analysis - Standoffs

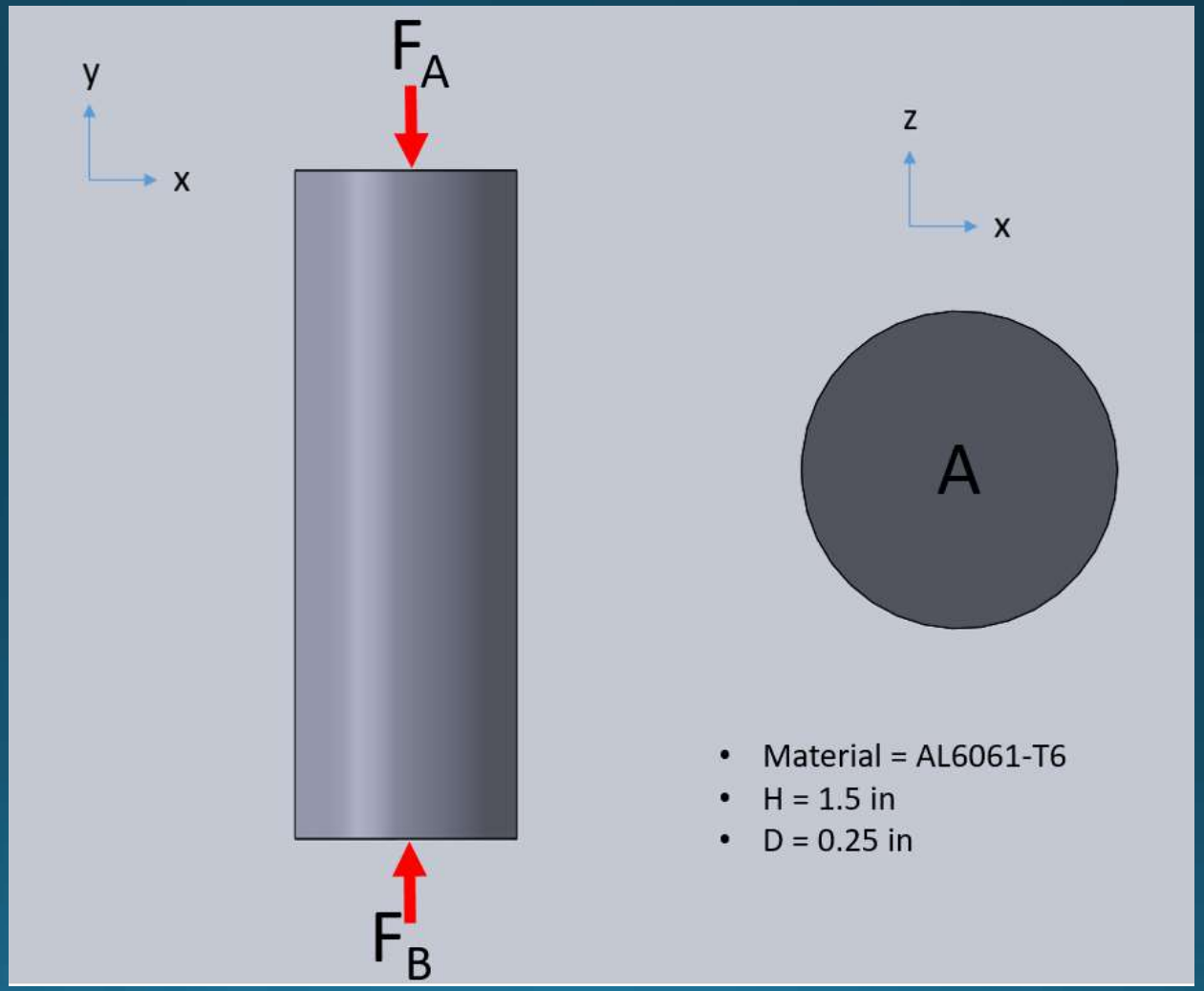
$$\sigma_{act} = \frac{F_A}{A}$$

$$FoS_{yield} = \frac{\sigma_{yield}}{\sigma_{act}}$$

$$\delta_y = \frac{F_A H}{AE}$$

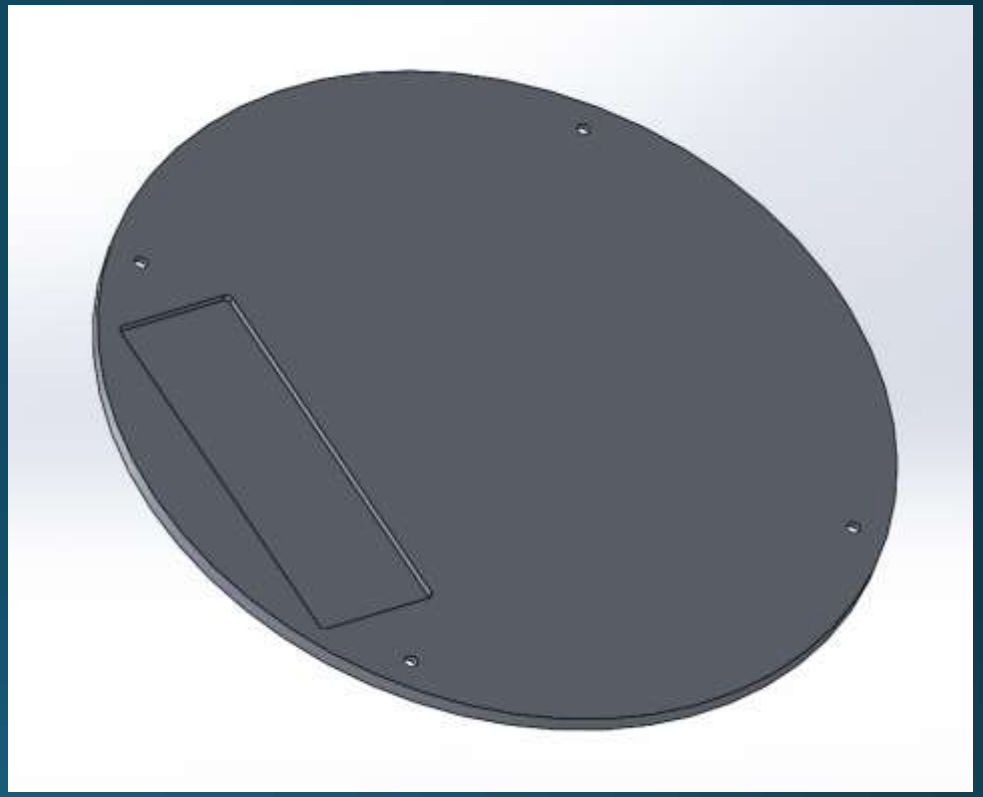
$$\sigma_{crit} = \frac{\pi^2 E}{\left(H/r\right)^2}$$

$$FoS_{crit} = \frac{\sigma_{crit}}{\sigma_{act}}$$



Structural Analysis - Plates

- Max Load: 1.6 lbs (assumed point mass, rectangular section between two posts)
- Max Normal Stress: 144.01 psi
- Material Yield Stress: 40 ksi
- Factor of Safety: 277
- Maximum Deflection: 5.40 x 10^-3 in

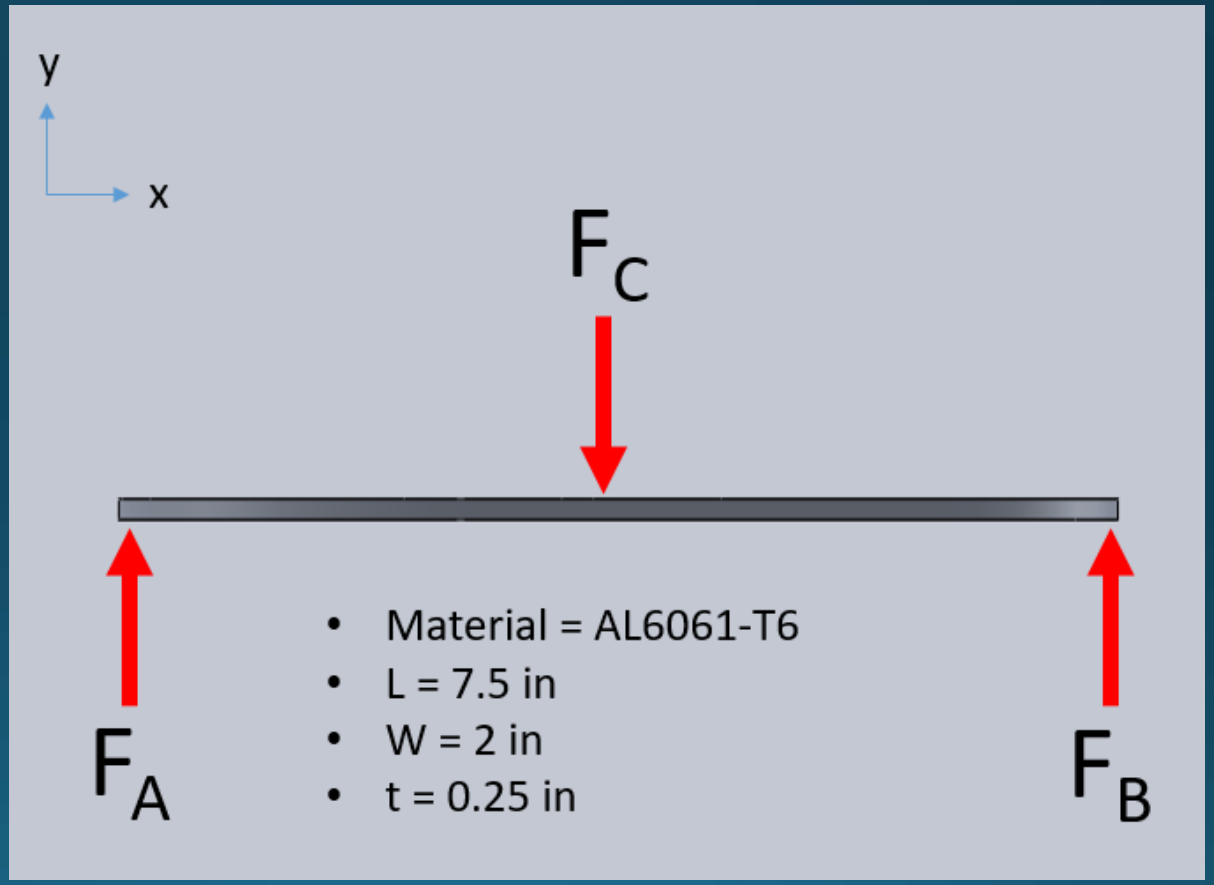


Structural Analysis - Plates

$$\sigma_{max} = \frac{Mc}{I_{zz}}$$

$$FoS = \frac{\sigma_{yield}}{\sigma_{max}}$$

$$y_{max} = -\frac{F_C L_{AB}^3}{48 E I_{zz}}$$



Structures BoM

Part	Quantity	Cost ($)	Mass (lb)
BasePlate	1		2.609
TopPlate	1		2.294
RWPlate	1		2.59
BearingPlate	1		1.218
PixyFrontPlate	1		0.045
PixyBackPlate	1		0.105
PixyMidPlate	1		0.076
MotorBracket	2		0.192
ThreadedHexStandoff	12	3.03 (each)	0.03
PixyAssemblySpacers	4	0.44 (each)	0.003
MotorAllignmentPins	6	6.00 (per 25)	0.001
10-32, 5/8 TorxFlatHeadScrew	16	10.03 (per 50)	0.006
4-40, 0.1875 BLACK-OXIDE ALLOY STEEL SOCKET HEAD CAP SCREW	12	8.12 (per 100)	0.001
6-32, 0.5 ALLOY STL TORX DRIVE FLAT-HEAD SCKT CAP SCREW	2	8.54 (per 50)	0.002
ReactionWheelDisk	2		
StationKeepingRod	1		
RodBlock	1		
Totals	n/a	70.81	9.172

Requirements Flow-down

1. The TestTable shall allow for two degrees of freedom in translation and one degree of freedom in rotation in a low friction environment.

    1.1. The TestTable shall allow for unrestricted rotation of the MockSat about its axis normal to the plane of the TestTable.

    1.2 The TestTable shall allow for translation along two orthogonal axes within a designated portion of the plane of the TestTable surface

        1.2.1 The TestTable shall utilize a station-keeping mechanism to restrict the translation of the MockSat to less than 1.0 inch.

    1.3 The TestTable shall support the weight of the MockSat whilst providing a reduced friction surface.

        1.3.1 The total rotational friction between the MockSat and the TestTable during nominal operation shall be no greater than 1.5 $\frac{lbm \cdot in^2}{s}$.

    1.4 The TestTable shall comply with OSHA Two-Man Lift Criteria

        1.4.1 The TestTable shall occupy a volume no greater than 72 x 72 x 28 inches.

        1.4.2 The TestTable shall weigh no more than 100 pounds

Requirements Flow-down

2. The MockSat shall be equipped with an attitude determination and control system (ADCS) that replicates the 0.04 Hz bandwidth response of the GOES-16 satellite to within 10%.
    - 2.1. The MockSat shall be equipped with two reaction wheels for rotational control.
        - 2.1.1. The MockSat reaction wheels shall be scaled/tuned to simulate the response of GOES-16 about its max MOI.
        - 2.1.2. The MockSat reaction wheels shall be capable of responding to user fault injection.
    - 2.2. MockSat shall have a sensor to provide rotational data.

Requirements Flow-down

3. The MockSat shall have the ability to maintain a controlled attitude relative to a point of reference within ±2.5°.
    3.1. The MockSat shall be equipped with a sensor array to determine its orientation.
        3.1.1. The MockSat shall have a coarse sensor to provide a wide field of view and get fine sensor in range.
        3.1.2. The MockSat shall have a fine sensor to determine attitude with an accuracy of ±2.5°.
        3.1.3. The MockSat shall maintain pointing accuracy for no less than 30 seconds.

Requirements Flow-down

4. The system shall have the ability to introduce a fatal operating fault in either the MockSat's primary reaction wheel, the coarse orientation sensor, or the fine orientation sensor (but not more than one fault at a time).

- 4.1. The fault injection system shall not cause permanent damage to the ADCS system
- 4.2. The fault injection system shall wait for user command from the ground station to initiate fault injection.
  - 4.2.1. The ground station unit shall allow the user to initiate a choice of reaction wheel fault, coarse sensor fault, or fine sensor fault.
    - 4.2.1.1. The fault injection system shall create a sensed increase in friction torque of 5.5 times the natural coulomb friction in the reaction wheel.
      - 4.2.1.1.1. The fault shall be injected as a feedback loop living on the microcontroller.
    - 4.2.1.2. The coarse and fine sensor shall be injected with a fault capable of introducing an error as a position bias.
  - 4.2.2. The ground station unit shall be able to send a command for fault initiation to the fault injection system.
- 4.3. The fault injection system shall be able to be deactivated by user command.
  - 4.3.1. The ground station unit shall allow the user to deactivate the fault injection system
  - 4.3.2. The ground station unit shall be able to send a command to deactivate the fault injection system.

Requirements Flow-down

5. The MockSat flight control software shall recover from a fatal operating fault in either the MockSat's primary reaction wheel or the fine orientation sensor (but not more than one fault at a time) by regaining normal operation.

5.1. There shall exist in software a fault management system to handle fault detection and identification.

5.1.1. The fault management system shall have the ability to detect a fatal operating fault from the reaction wheel.

5.1.2. The fault management system shall have the ability to detect a fatal operating fault from the coarse attitude sensor.

5.1.3. The fault management system shall have the ability to detect a fatal operating fault from the fine attitude sensor.

5.1.4. The fault management system shall be independent of the fault injection system existence.

5.1.5. The fault management system shall classify the location of the fault (either reaction wheel, coarse attitude sensor, or fine attitude sensor).

5.1.6 The fault management system shall recover nominal operation of the satellite in the presence of a fault.

5.1.5.1. The fault management system shall be able to communicate with the power regulation board.

5.1.5.2. The fault management system shall be able to control power to the primary reaction wheel.

5.1.5.3. The fault management system shall be able to control power to the secondary reaction wheel.

5.1.5.4. The fault management system shall be able to switch sensing to a secondary attitude sensor.

5.1.6. The fault management system shall alert the ground station operator that a fatal fault has occurred.

5.1.6.1. The fault management system shall be able to alert the ground station operator to the type of fault that has occurred.

5.1.6.2. The fault management system shall be able to communicate with the Ground Station Unit

References

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