Preliminary Design Review

Lockheed Martin
LLAMAS Team

sateLLite ADCS fault MAnagement System

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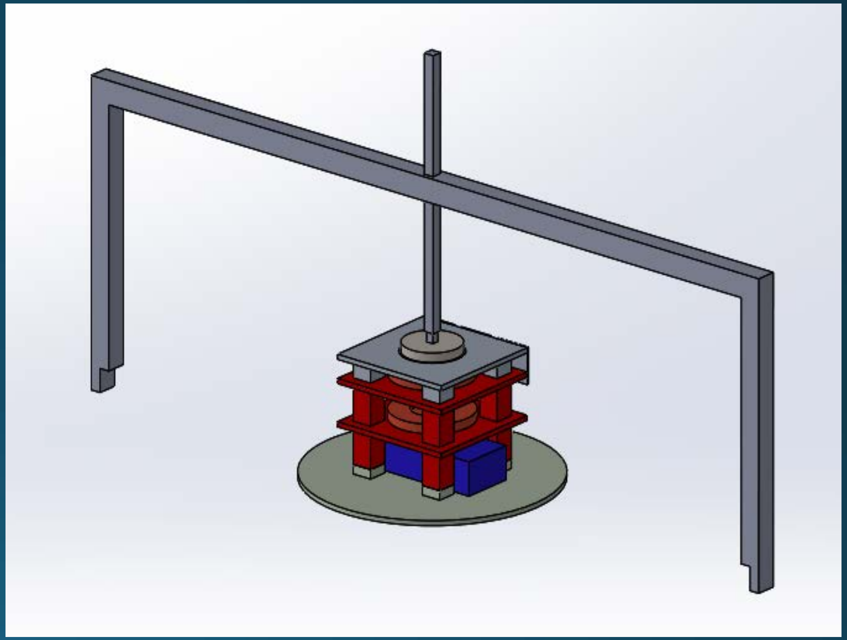
Project Statement

- The team will develop a fault management test bed which allows for testing of fault management software by fault injection into the attitude determination and control system (ADCS) of a mock-satellite (MockSat).
- The MockSat will be representative of the GOES-16 satellite, capable of relaying telemetry and fault data to a ground station unit, allow user selection of faults, and will be tested on a reduced-friction TestTable.

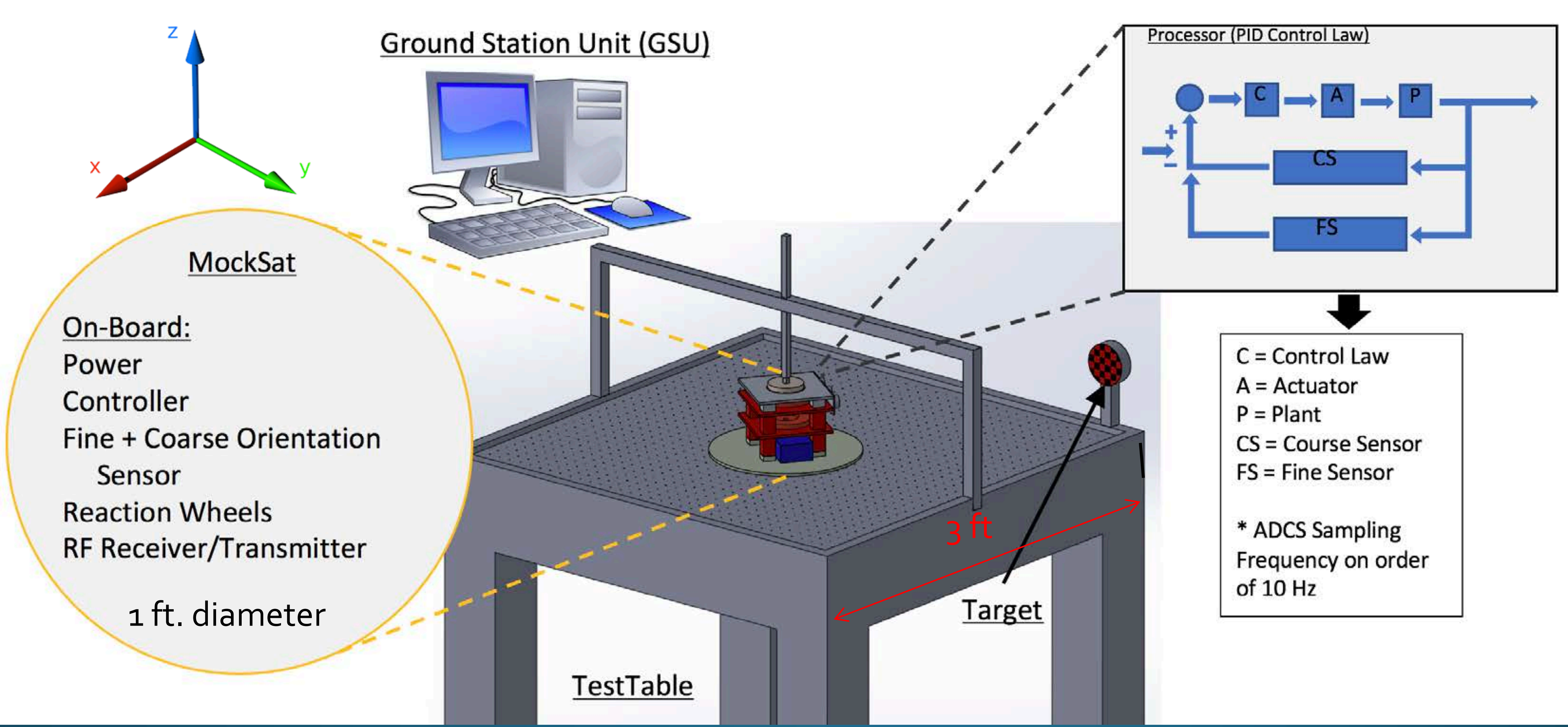
ADCS: Station Keeping– CDD Changes

- New Station Keeping Design
  - Bearing on top plate of MockSat
  - Rod inserted into bearing which achieves Station Keeping
- In CDD, trade study resulted in a tie between magnetic ring and string attachment
- After discussion with PAB, magnetic ring idea was dismissed
  - Difficulty of implementation higher than expected
  - Difficulty of modeling, feasibility
- String idea was developed further
  - Realized torsion in string will impact dynamics
  - Will have pendulum dynamics

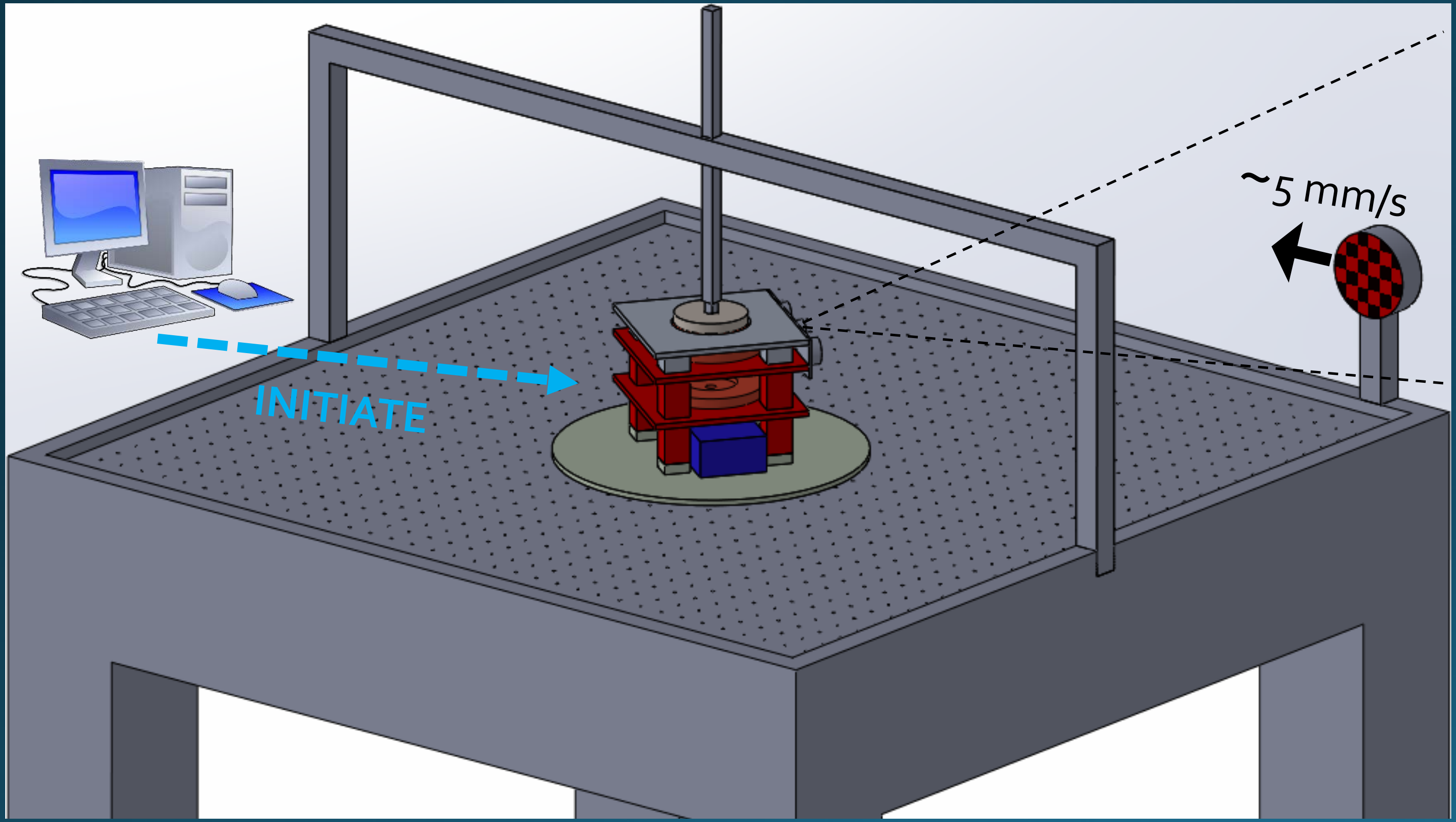
<u>Selected Design</u>
Rod and Bearing Station Keeping



Concept of Operations (CONOPs)



CONOPs



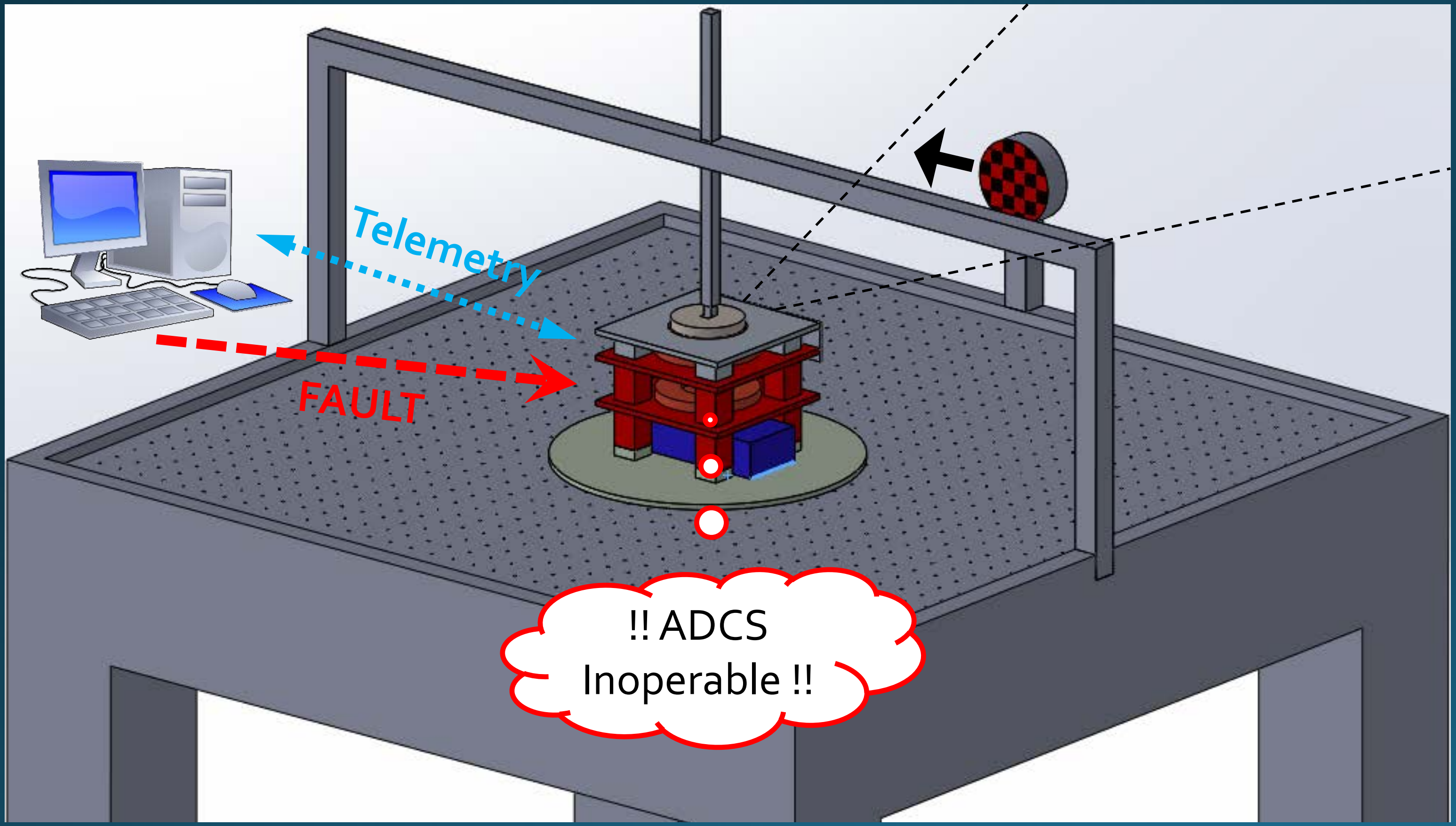
1. Test initiation and startup

1.1 Ground station unit (GSU) activates MockSat.

1.2 MockSat scans surroundings for the reference target.

1.3 MockSat maintains orientation relative to reference target once acquired to ± 2.5 degrees .

CONOPs



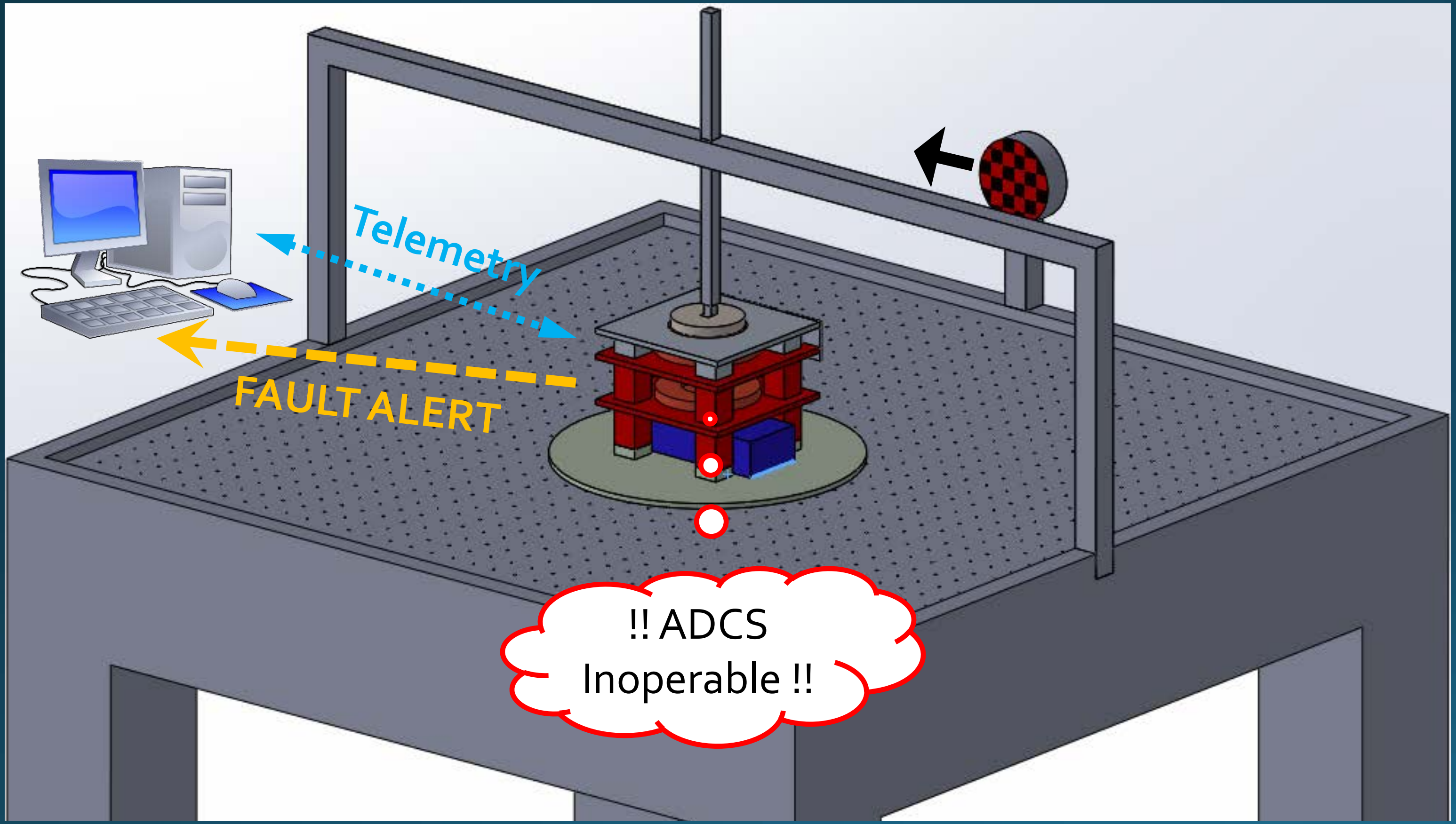
2. <u>Fault Injected by User</u>

2.1 User selects fault to inject from list of options on GSU and sends command to fault injection system.

2.2 Fault injection, on Micro-Controller Unit (MCU), system initiates fault.

2.3 Injected fault prevents ADCS system from meeting nominal pointing requirements .

CONOPs

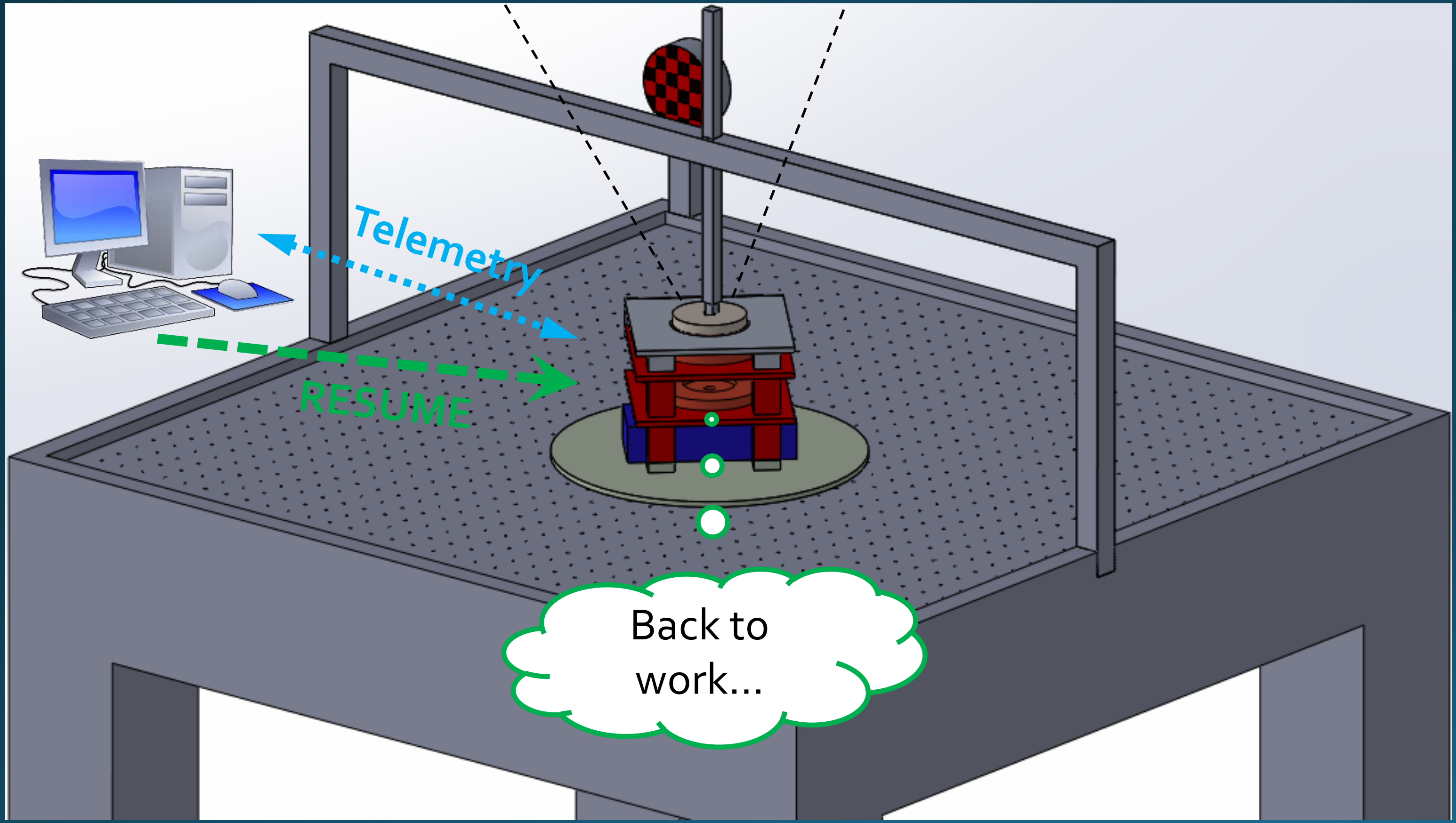


3. Fault Management

3.1 Fault management software on MockSat detects, characterizes, and identifies the fault.

3.2 Fault management software alerts user to presence and type of fault.

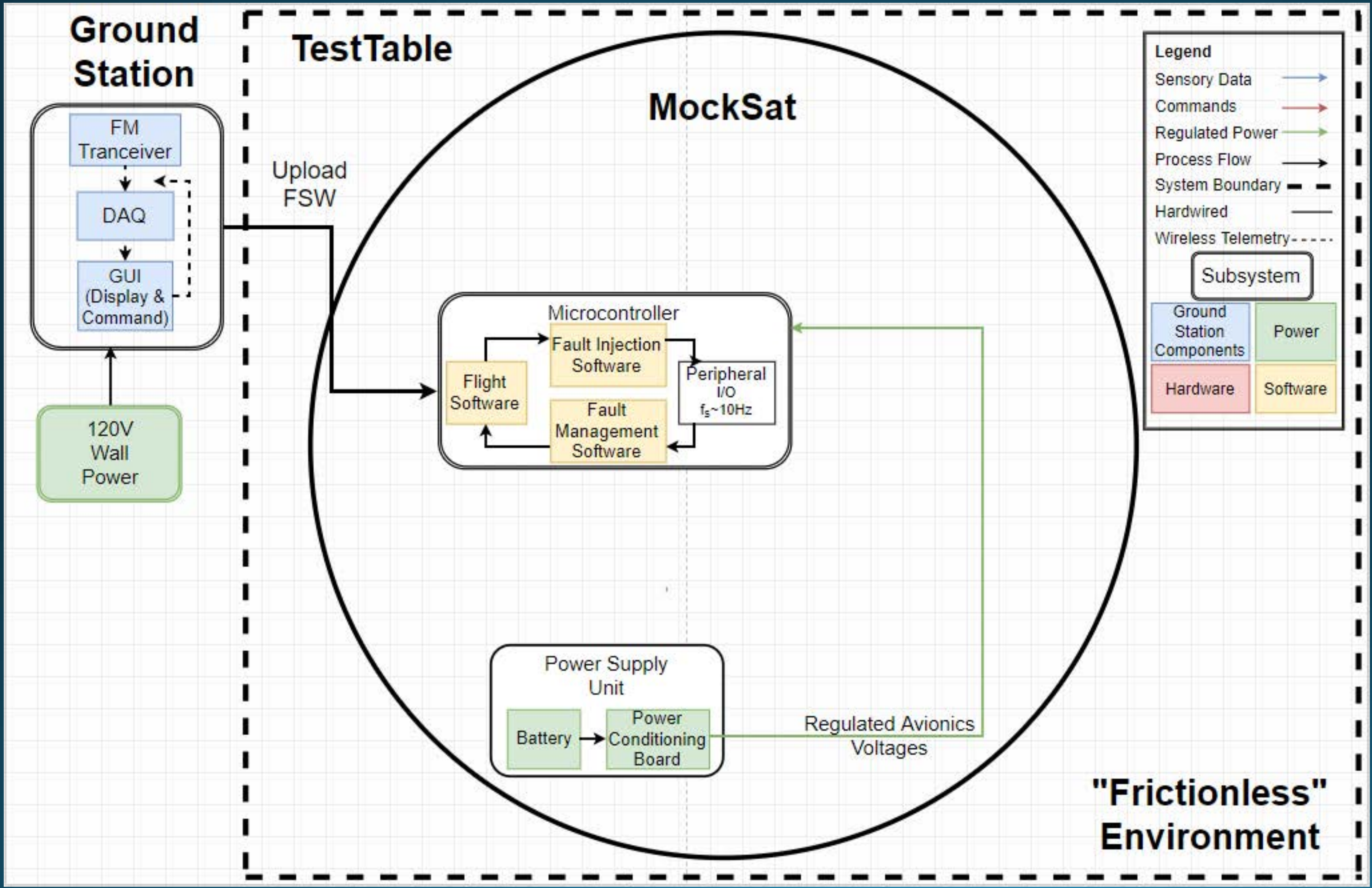
CONOPs



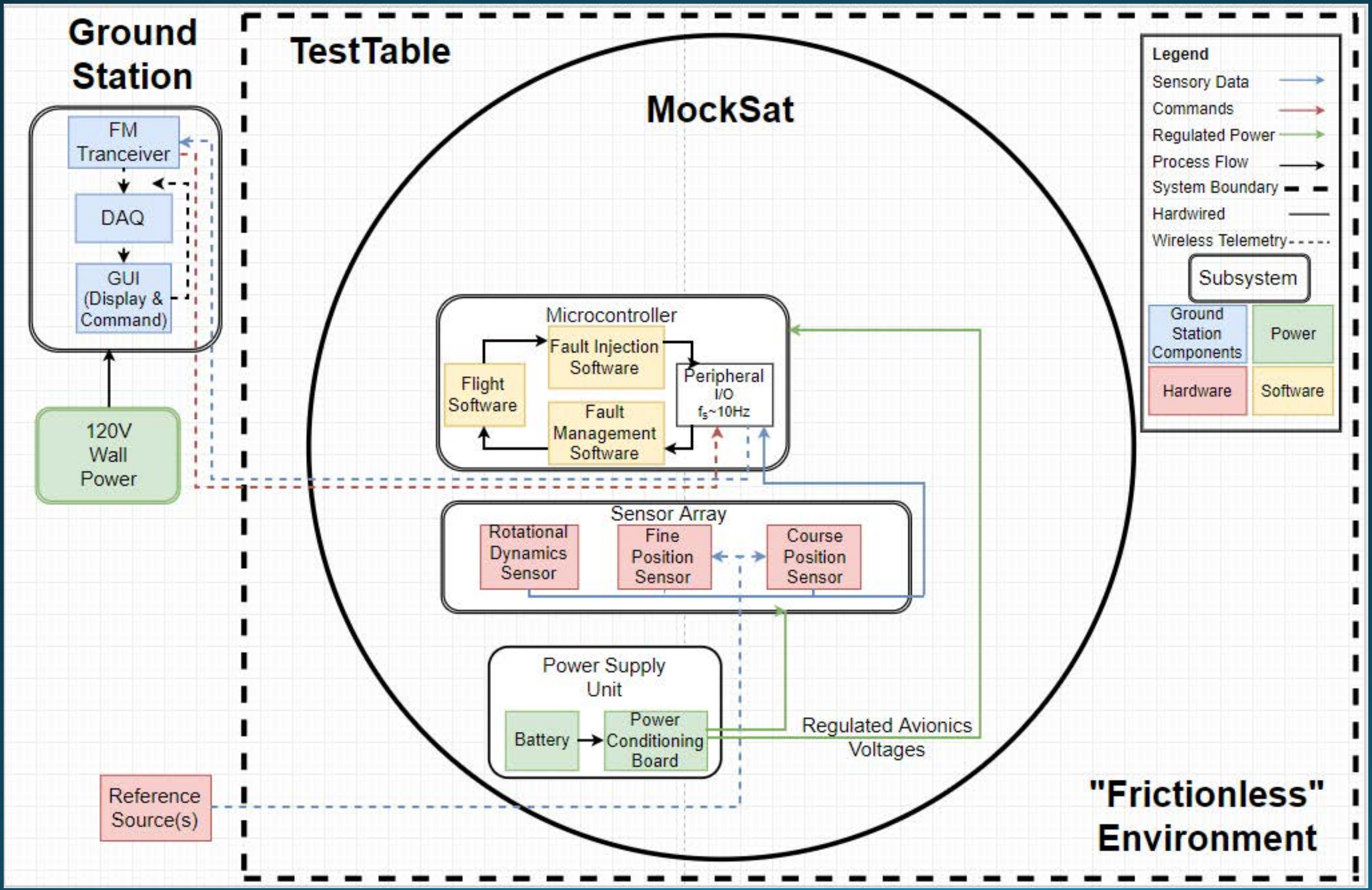
4. <u>Recovery</u>

4.1 Fault management software initiates recovery sequence.

4.2 Satellite returns to nominal operation.



Ground Station
TestTable
MockSat
FM Tranceiver
DAQ
GUI (Display & Command)
Upload FSW
120V Wall Power
Microcontroller
Flight Software
Fault Injection Software
Fault Management Software
Peripheral I/O f_s~10Hz
Power Supply Unit
Battery
Power Conditioning Board
Regulated Avionics Voltages
Legend
Sensory Data
Commands
Regulated Power
Process Flow
System Boundary
Hardwired
Wireless Telemetry
Subsystem
Ground Station Components
Power
Hardware
Software
"Frictionless" Environment


Ground Station
FM Tranceiver
DAQ
GUI (Display & Command)
120V Wall Power
Reference Source(s)
TestTable
MockSat
Microcontroller
Flight Software
Fault Injection Software
Fault Management Software
Peripheral I/O f_s~10Hz
Sensor Array
Rotational Dynamics Sensor
Fine Position Sensor
Course Position Sensor
Power Supply Unit
Battery
Power Conditioning Board
Regulated Avionics Voltages
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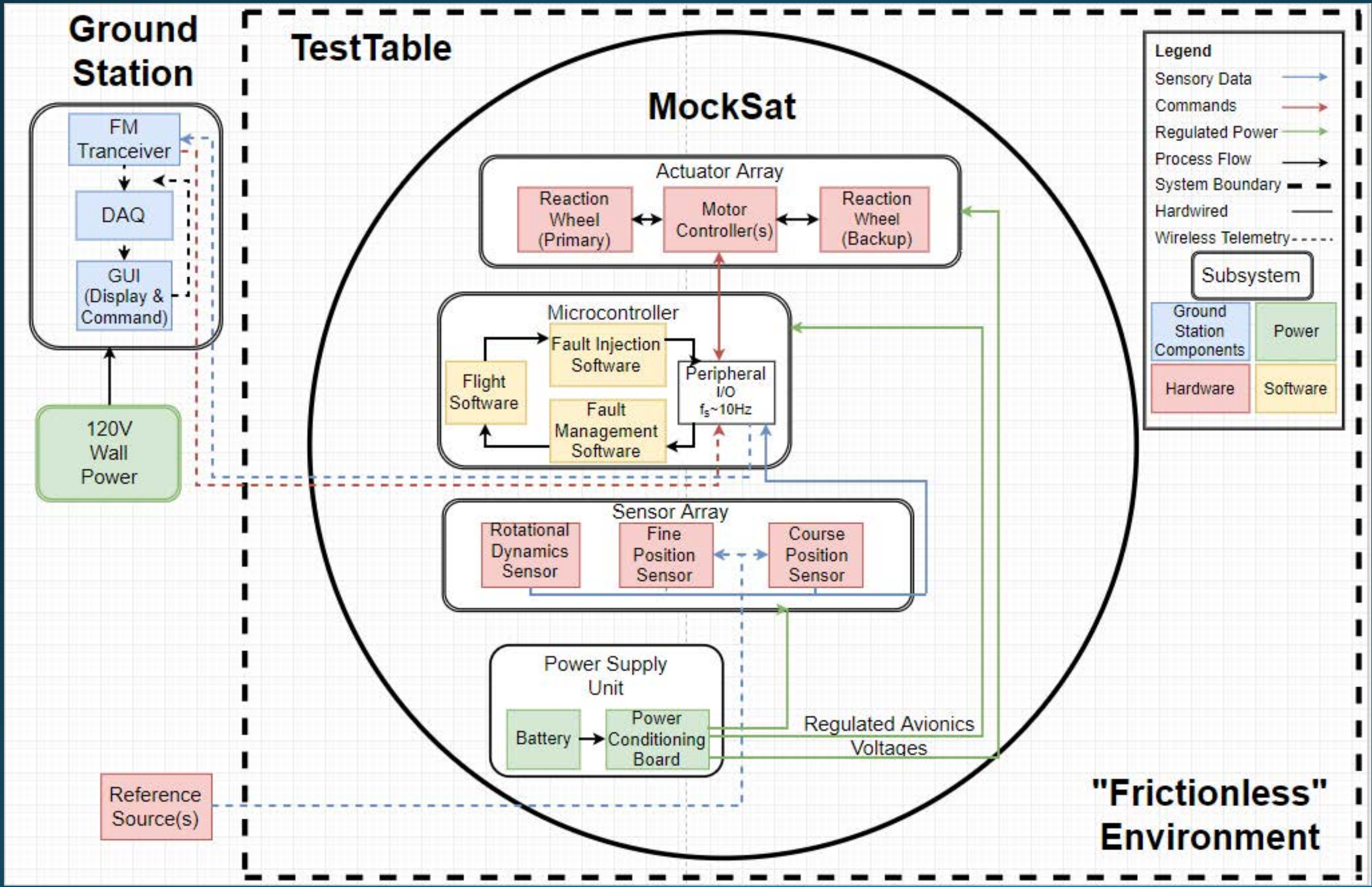
Ground Station
FM Tranceiver
DAQ
GUI (Display & Command)
120V Wall Power
Reference Source(s)
TestTable
MockSat
Actuator Array
Reaction Wheel (Primary)
Motor Controller(s)
Reaction Wheel (Backup)
Microcontroller
Flight Software
Fault Injection Software
Fault Management Software
Peripheral I/O f_s~10Hz
Sensor Array
Rotational Dynamics Sensor
Fine Position Sensor
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Power Supply Unit
Battery
Power Conditioning Board
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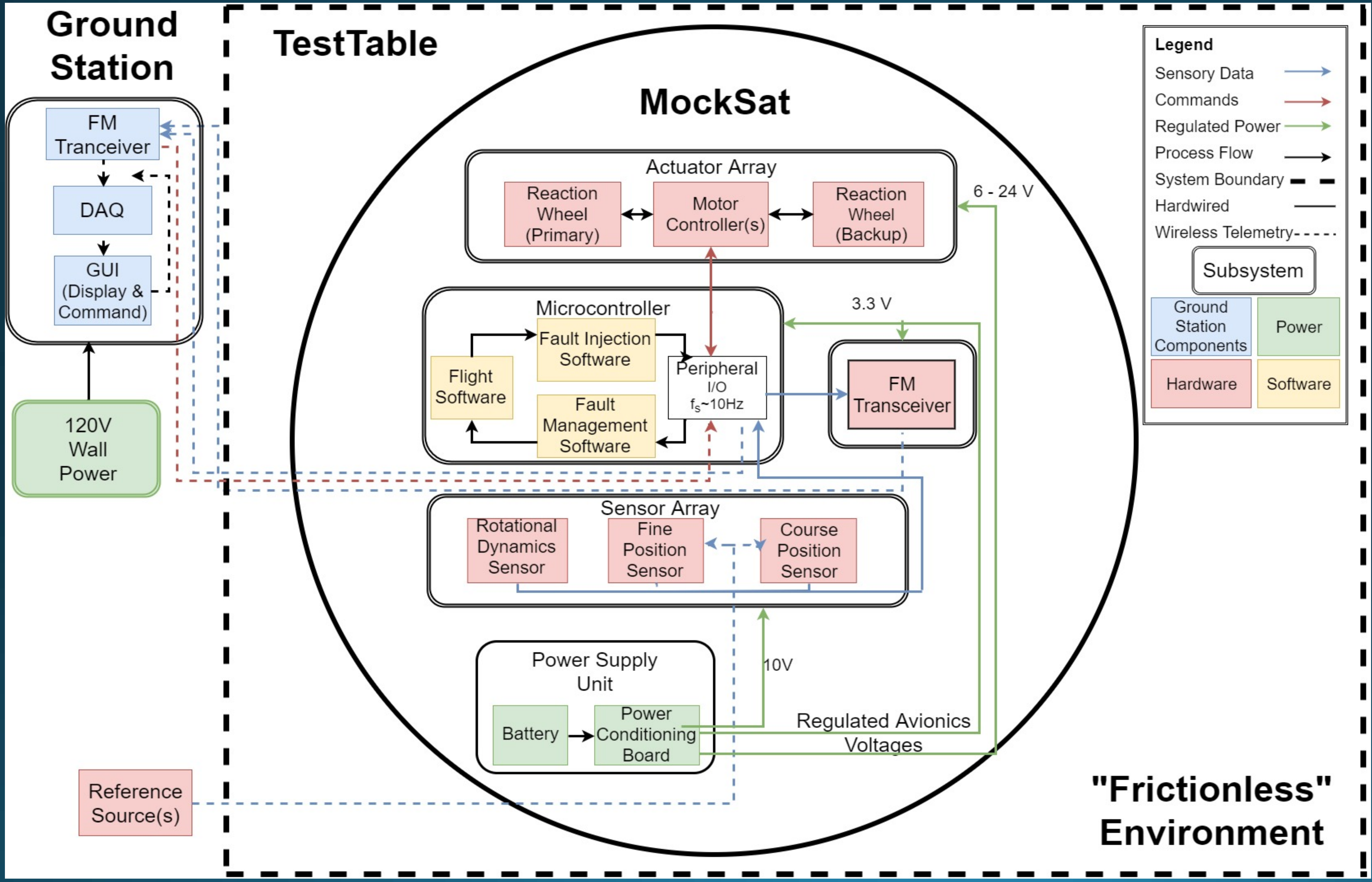
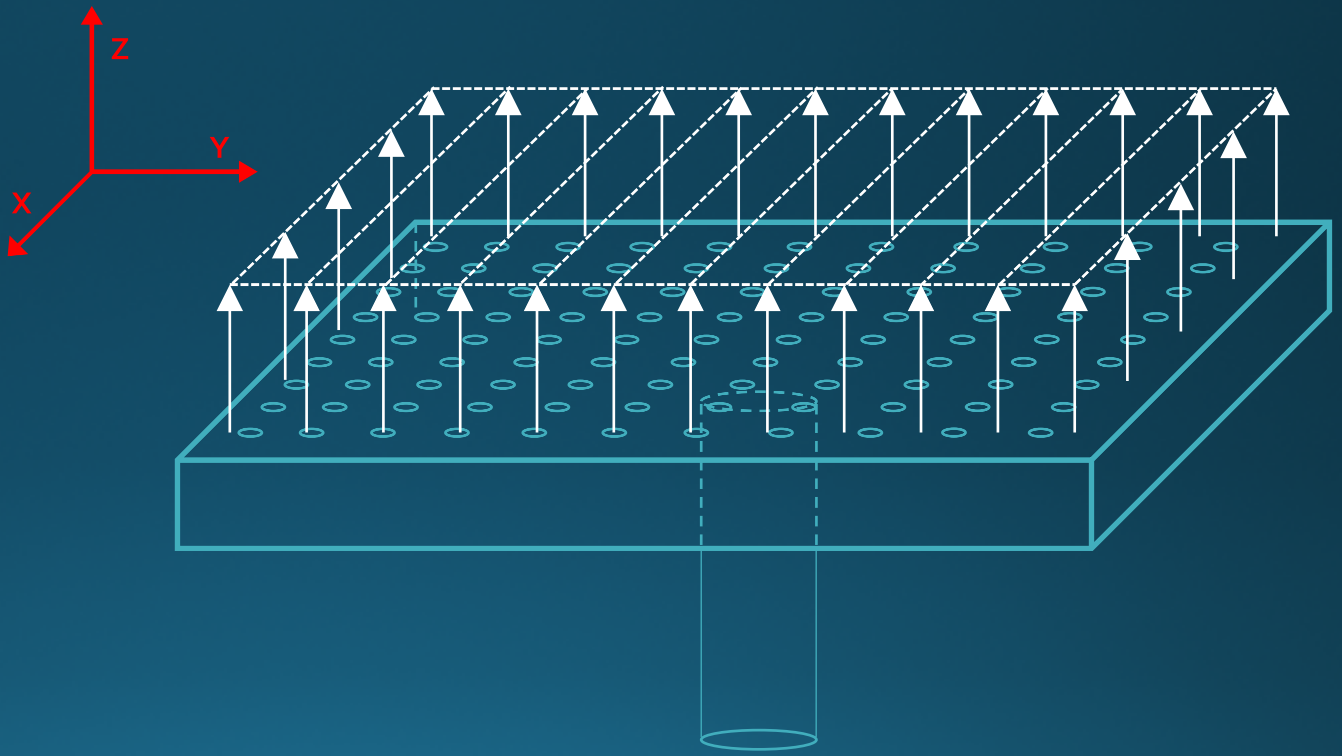

Ground Station
FM Tranceiver
DAQ
GUI (Display & Command)
120V Wall Power
Reference Source(s)
TestTable
MockSat
Actuator Array
Reaction Wheel (Primary)
Motor Controller(s)
Reaction Wheel (Backup)
6 - 24 V
Microcontroller
Flight Software
Fault Injection Software
Fault Management Software
Peripheral I/O f_s~10Hz
3.3 V
FM Transceiver
Sensor Array
Rotational Dynamics Sensor
Fine Position Sensor
Course Position Sensor
10V
Power Supply Unit
Battery
Power Conditioning Board
Regulated Avionics Voltages
Legend
Sensory Data
Commands
Regulated Power
Process Flow
System Boundary
Hardwired
Wireless Telemetry
Subsystem
Ground Station Components
Power
Hardware
Software
"Frictionless" Environment

Baseline Design – TestTable

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

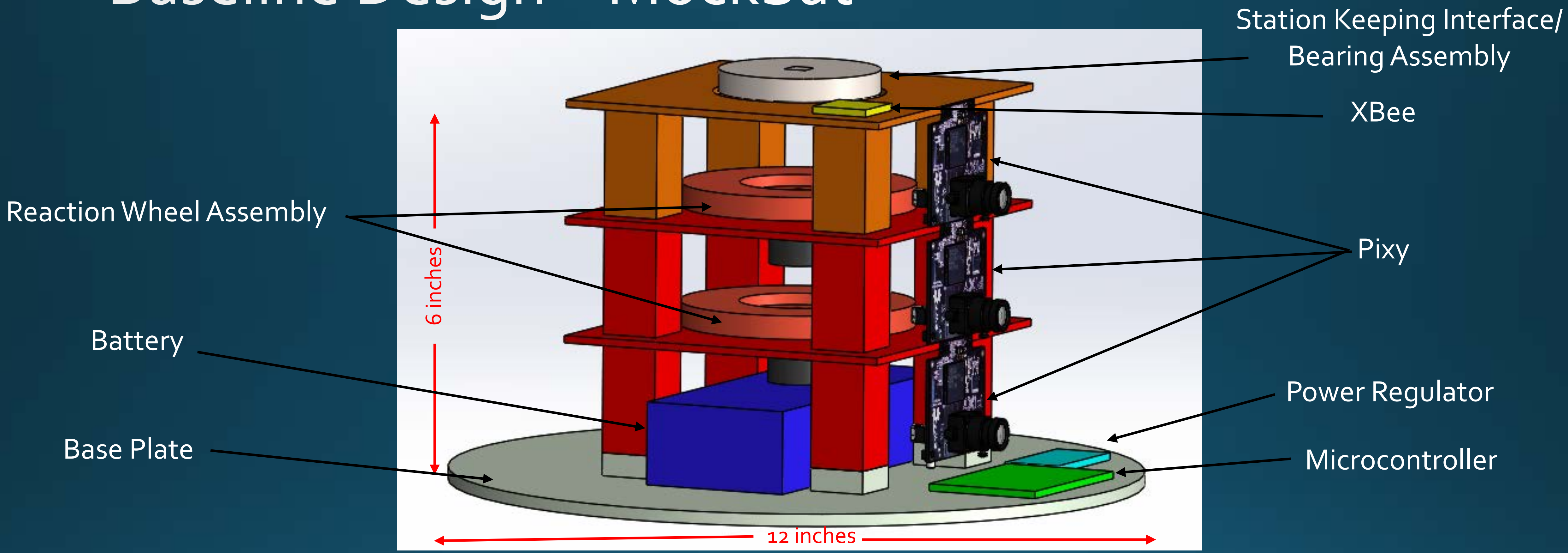
<u>Air table:</u>

- 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].



1.0	Project Overview, CONOPS, & FBD	*Kristyn S., Zach R.*
2.0	**Baseline Design**	
2.1–	TestTable	*Andrew M.*
2.2–	**MockSat**	***Andrew M.***
2.3–	Fault Injection and Management	*Corwin S.*
3.0	Critical Project Elements (CPEs)	
3.1 –	Fault Management and Injection System	
3.1.1	Reaction Wheel Fault	*Corwin S.*
3.1.2	Sensor Faults	*Pol S.*
3.2–	ADCS	
3.2.1	Sensors	*Dalton A.*
3.2.2	Actuators	*Zach R.*
3.2.3	Controls	*Dalton A.*
4.0	Status Summary, Plan of Action	*Kristyn S.*
5.0	Q & A	*LLAMAS*

Baseline Design – MockSat



Functional Requirements:

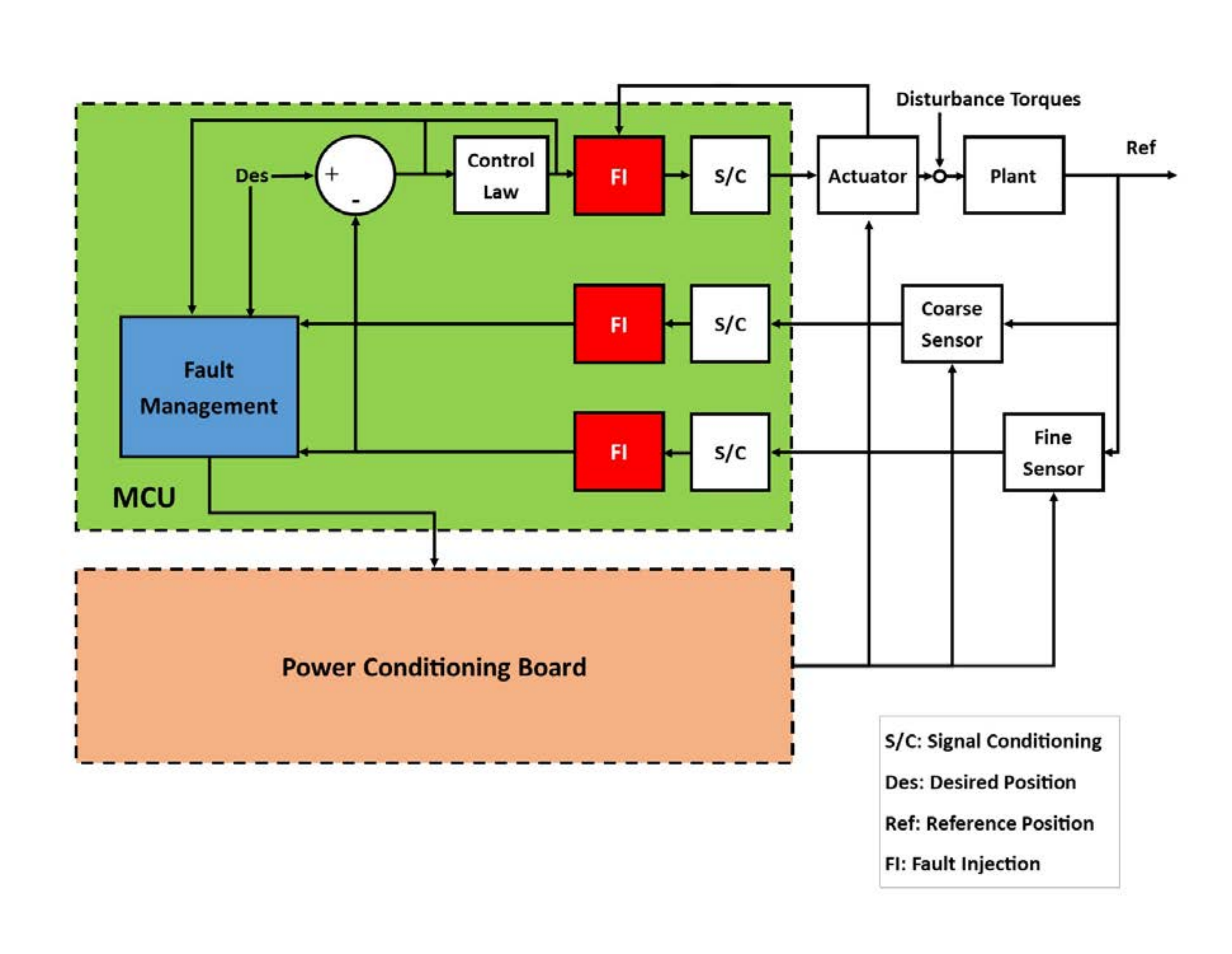
- The MockSat shall be equipped with an attitude determination and control system (ADCS) that replicates the 0.04 Hz bandwidth response of the GOES-16 satellite to within ±10%.
- The MockSat shall have the ability to maintain a controlled attitude relative to a point of reference within ±2.5°.

Baseline Design – Fault Injection & Management System

Functional Requirements:

- *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**).*
- *The MockSat flight control software shall **recover from 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) by **regaining nominal operation**.*

Baseline Design – Fault Injection & Management System: Overview



FBD of ADCS MCU with fault injection and fault management systems

Fault Injection:

- Fault Injection lies in software
- Injection system can modify:
  - Command torque to reaction wheel
  - Data streams from coarse sensor
  - Data streams from fine sensor
- Injection receives commands via comms from GSU to initiate fault injection

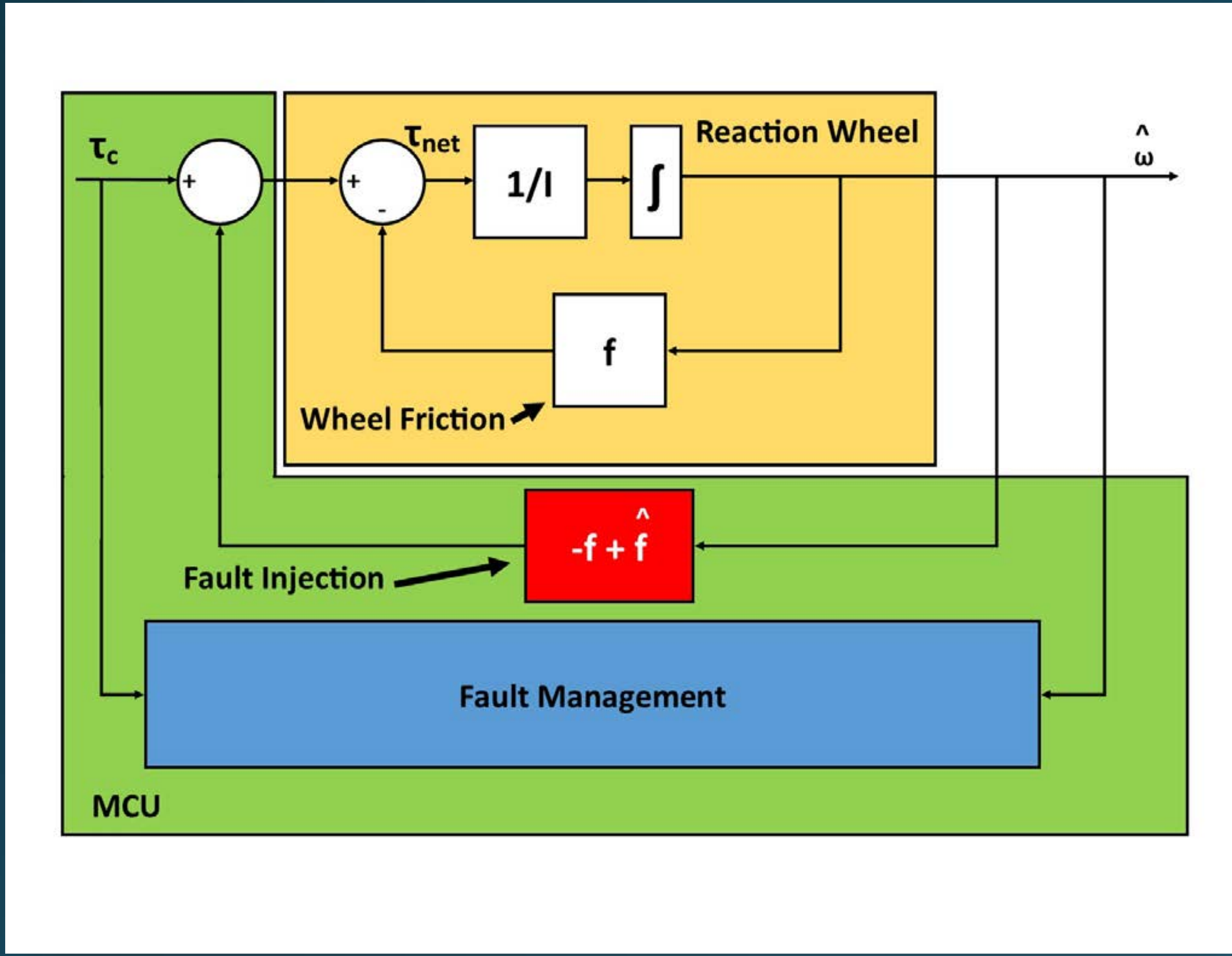
Fault Management:

- Fault Management system lies in software
- Fault Management detects faults by examining data streams
- Management can control power to:
  - Attitude actuators
  - Attitude sensors
- Management alerts GSU of fault detection via comms, fixes fault by switching to redundant components

CPE-Fault Injection and Management System: Overview

- In order to meet functional requirements for fault injection, the injection system needs to:
  - Inject at least one fault into each of: the reaction wheel, the coarse sensor, and the fine sensor
- In order to meet functional requirements for fault management, the management system needs to:
  - Detect and classify faults in each of: the reaction wheel, the coarse sensor, and the fine sensor
  - Regain nominal operation. Do not need "bump-less" switching or high performance recovery.

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:

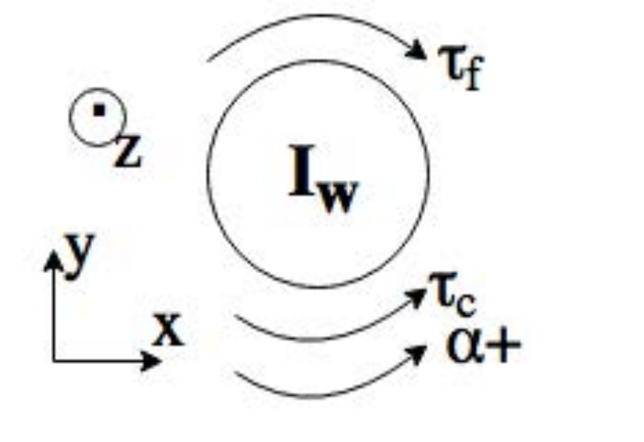
$$\tau_f = f(\omega)$$

- Induced friction function:

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

Fault Management: Reaction Wheel Friction

Model:



Reaction wheel dynamics

- Governing Equation:

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

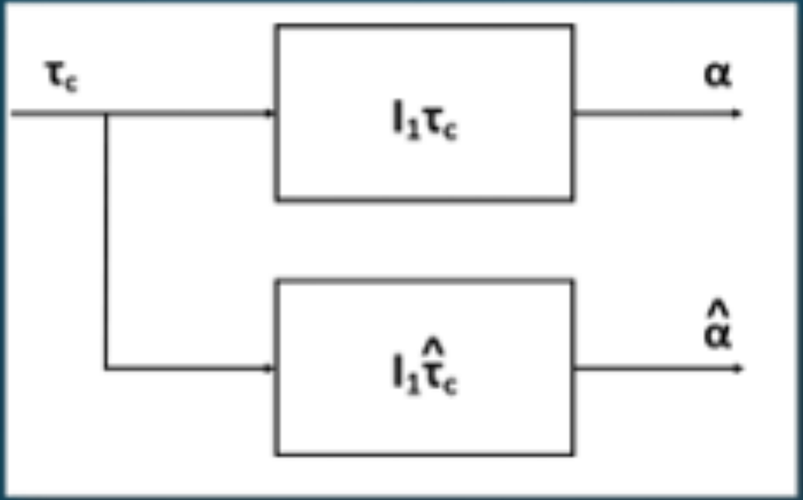
- Nominal friction:

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

- Induced Friction:

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

Detection:



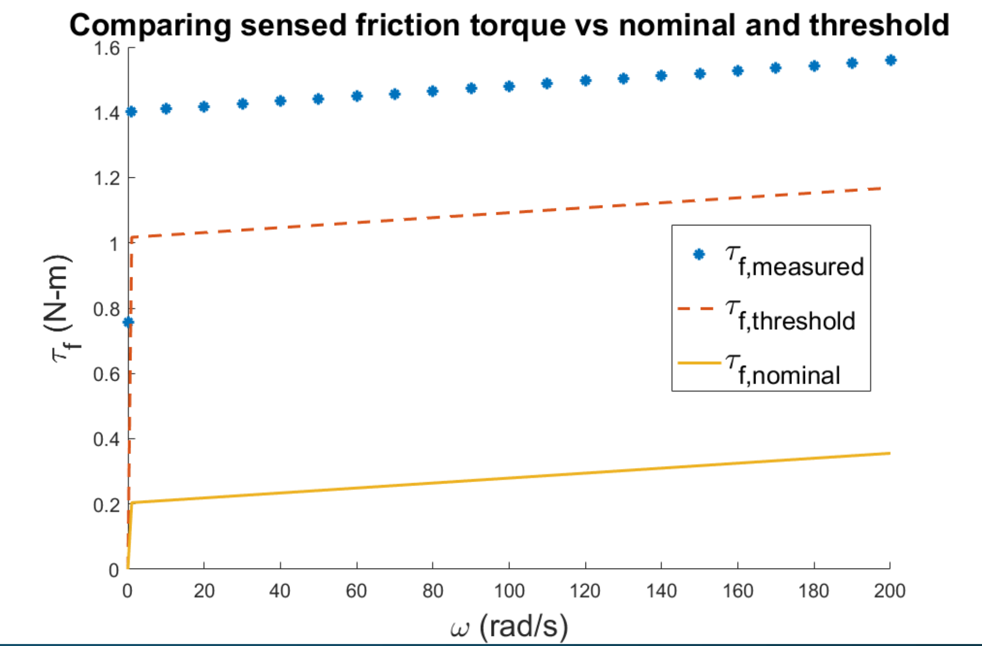
Comparison between model and actual

- 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:

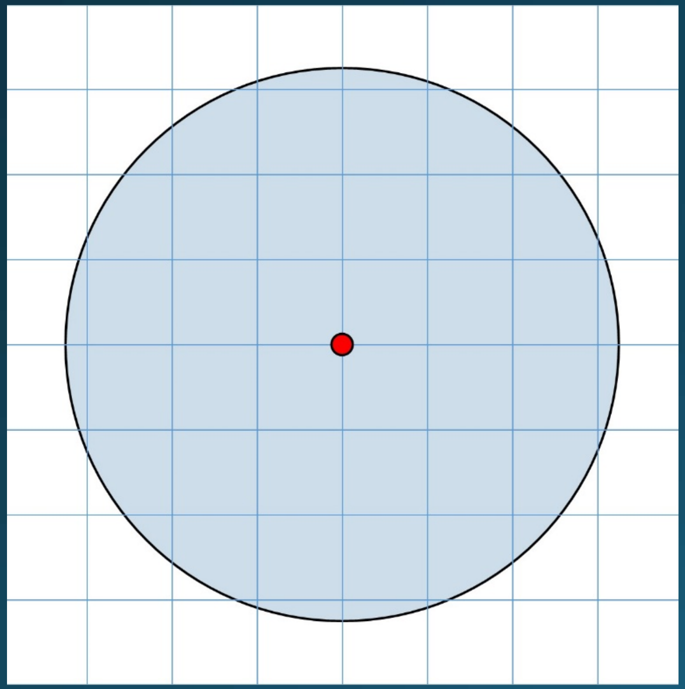


- ASEN 3200 spin module data used to create nominal friction function
- Induced friction function used to inject fault
- Modeled using governing equation and Matlab's ode45 solver
- Friction in system is greater than threshold value, therefore **this is feasible**

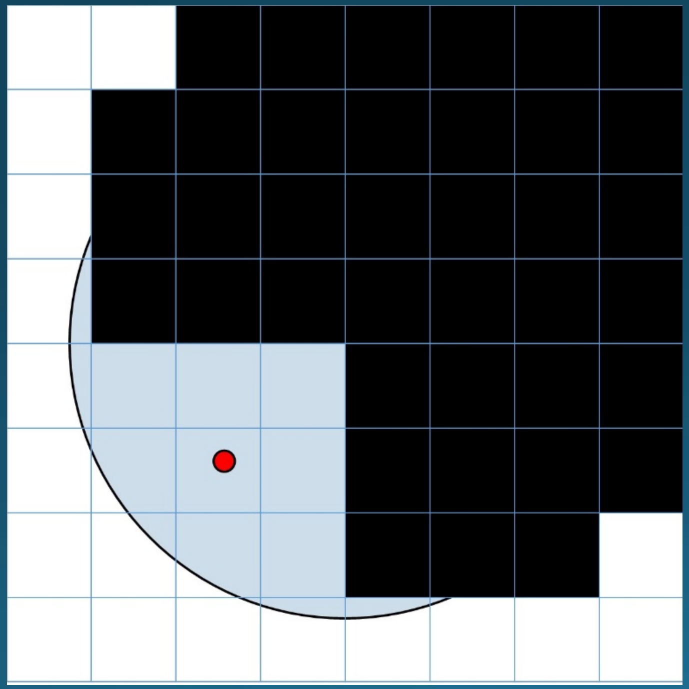
Fault Injection and Management System: Sensors

The question is "how many pixels would need to go 'hot' for enough bias in the sensor to flag a fault?"

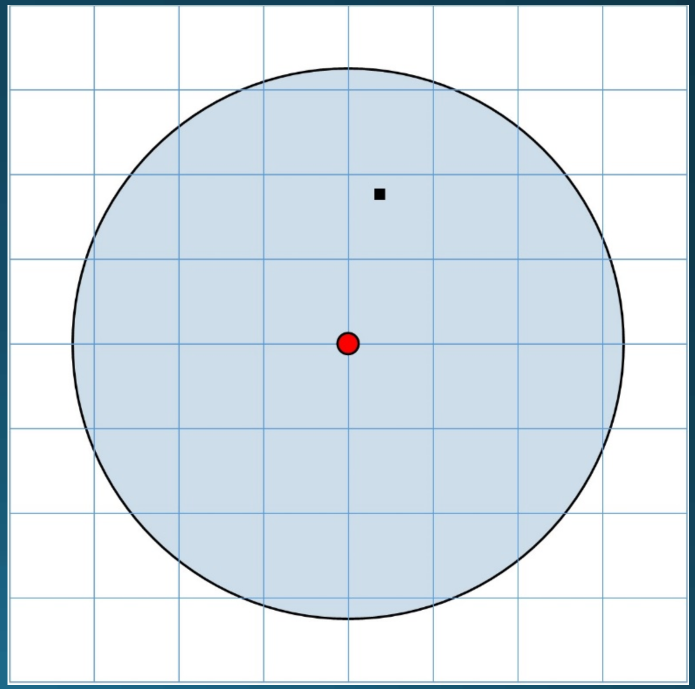
No failure



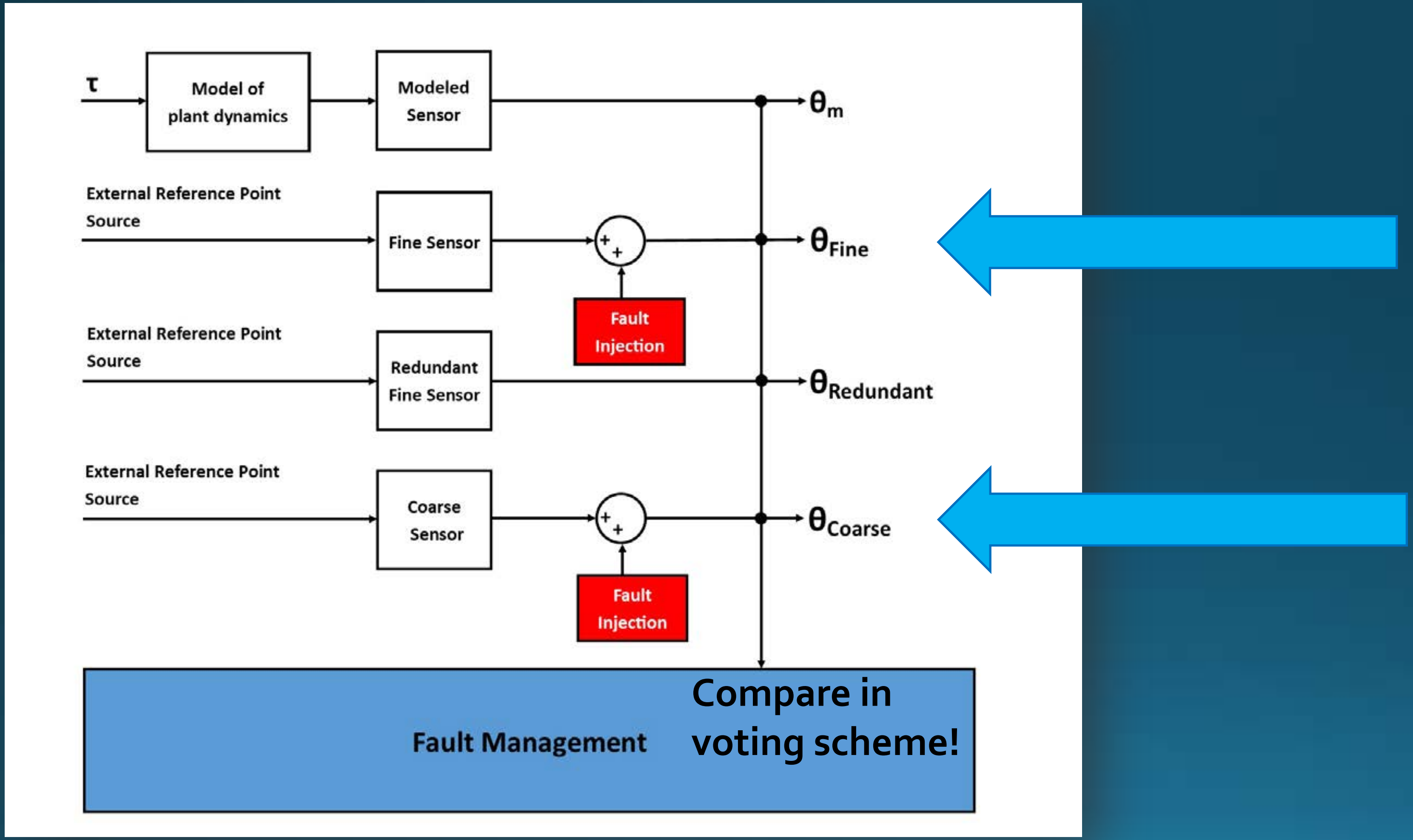
Extreme failure



Subtle failure



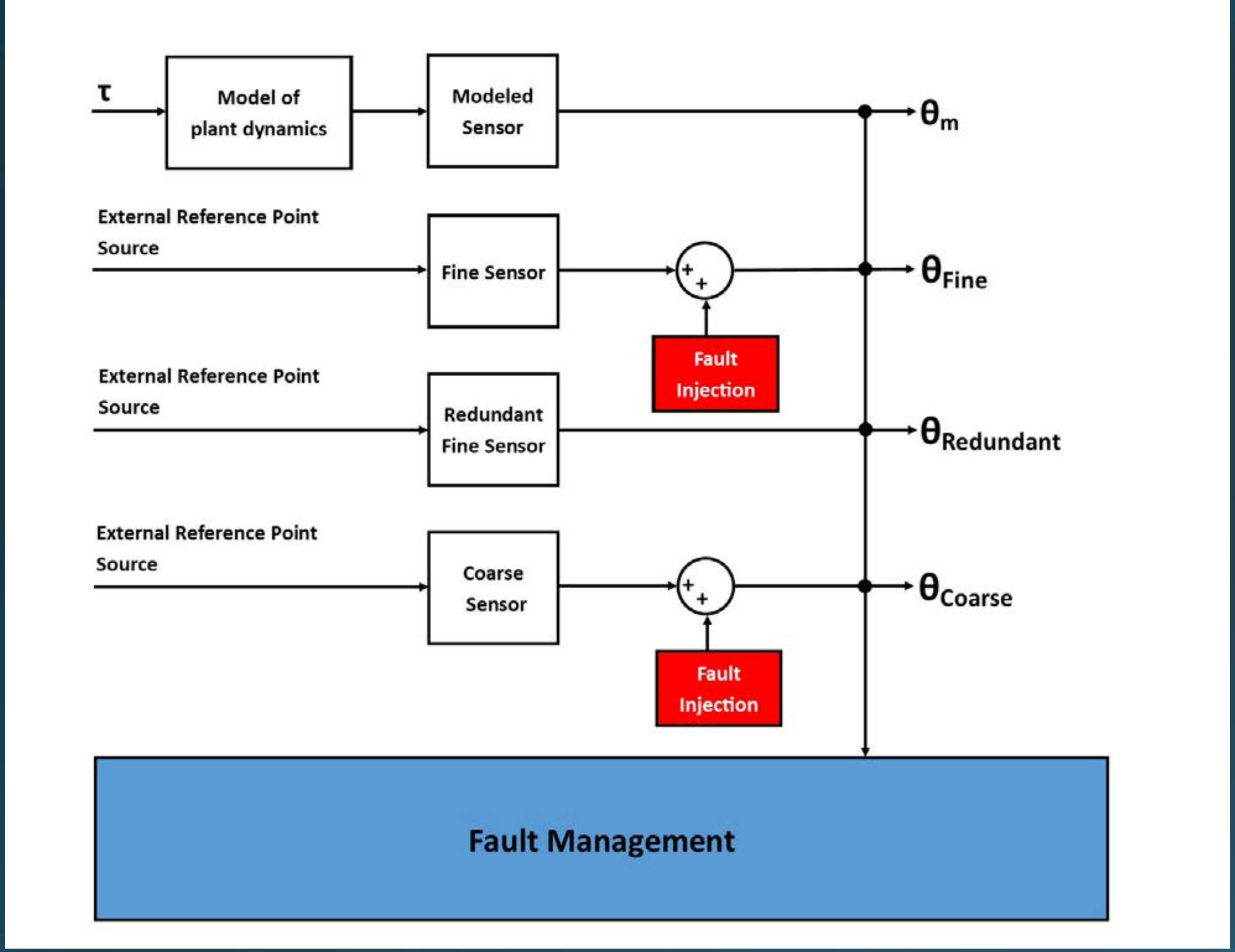
Fault Injection and Management System: Sensors



FBD of sensor system with fault injection and fault management systems

After injecting fault, will the faulty positions given by the fine and coarse sensor be large enough to detect a fault?

Fault Injection and Management System: Sensors



FBD of sensor system with fault injection and fault management systems

Yes! Based off project requirements only 1 fault needs to be injected into the fine and coarse sensor.

This fault is up to the team to decide. The size of the fault can always be increased to resemble a larger pixel failure. **This is feasible.**

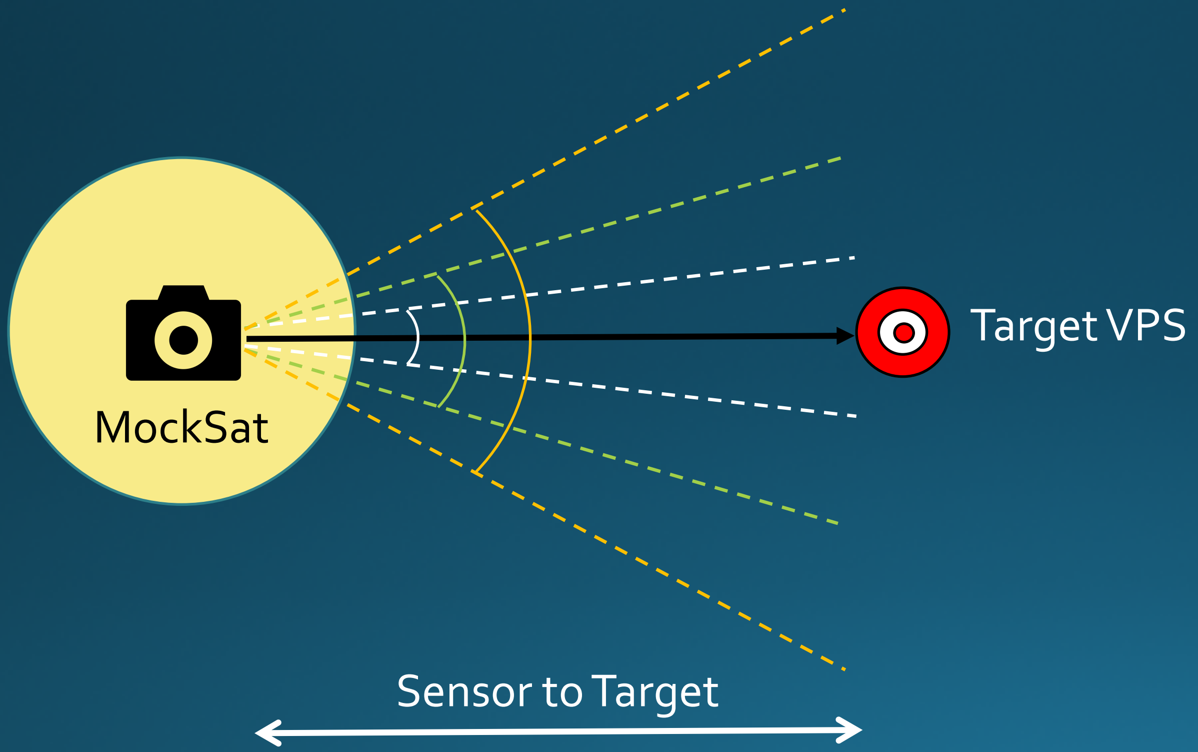
CPE – Attitude Determination and Control System

- Elements of ADCS
  - Station Keeping
  - Sensors
  - Bandwidth of system
  - Capability of actuators

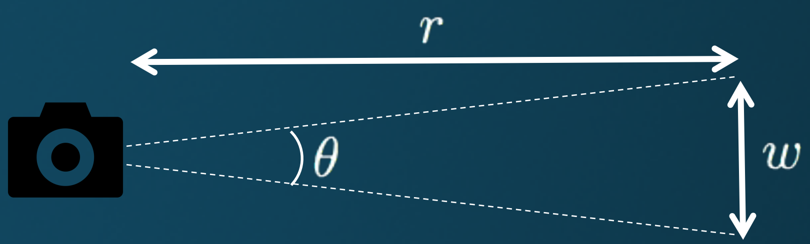
- Why attitude control is a CPE:
  - ADCS is fundamental to the ability to test fault management. It provides a nominal state that can prove fault management works as intended before and after a fault is injected

ADCS: Sensors

Target Pointing Window	5^o
Fine Attitude Sensor Field of View	$[10^o, 25^o]$
Coarse Attitude Sensor Field of View	$[40^o, 75^o]$



$$r \in [0.30, 0.60]\ m$$



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

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

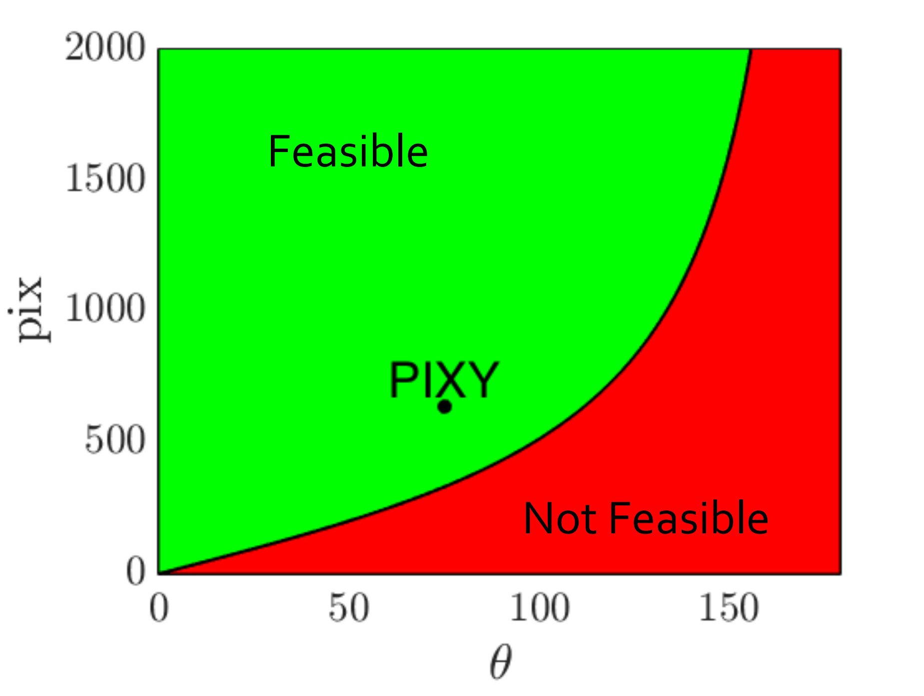
ADCS: Sensors

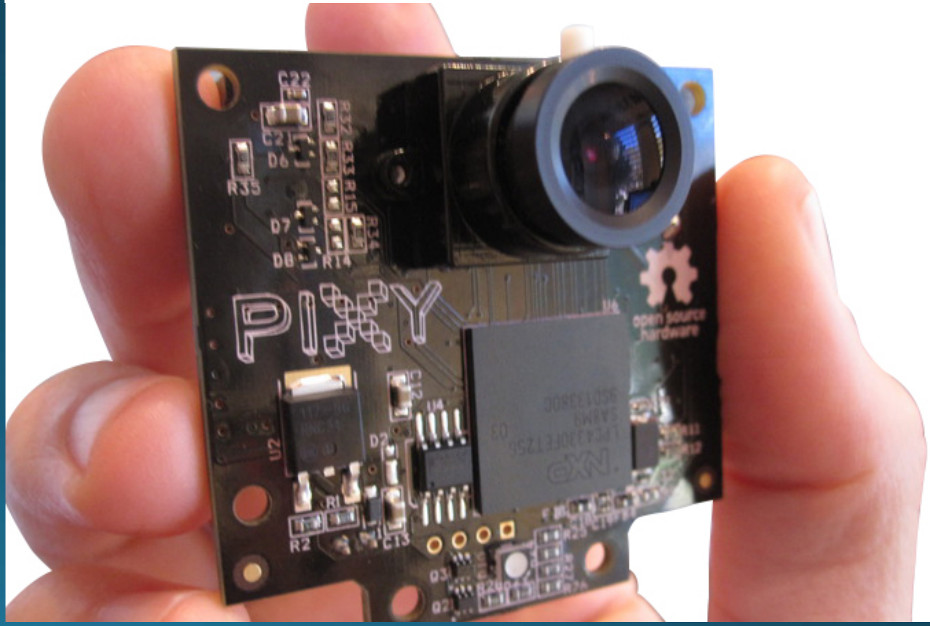
Fine Camera Resolution:

$$\Xi_f = \frac{max(w_f)}{L_{min}} = 98\ pixels$$

Coarse Camera Resolution:

$$\Xi_c = \frac{max(w_c)}{L_{min}} = 337\ pixels$$





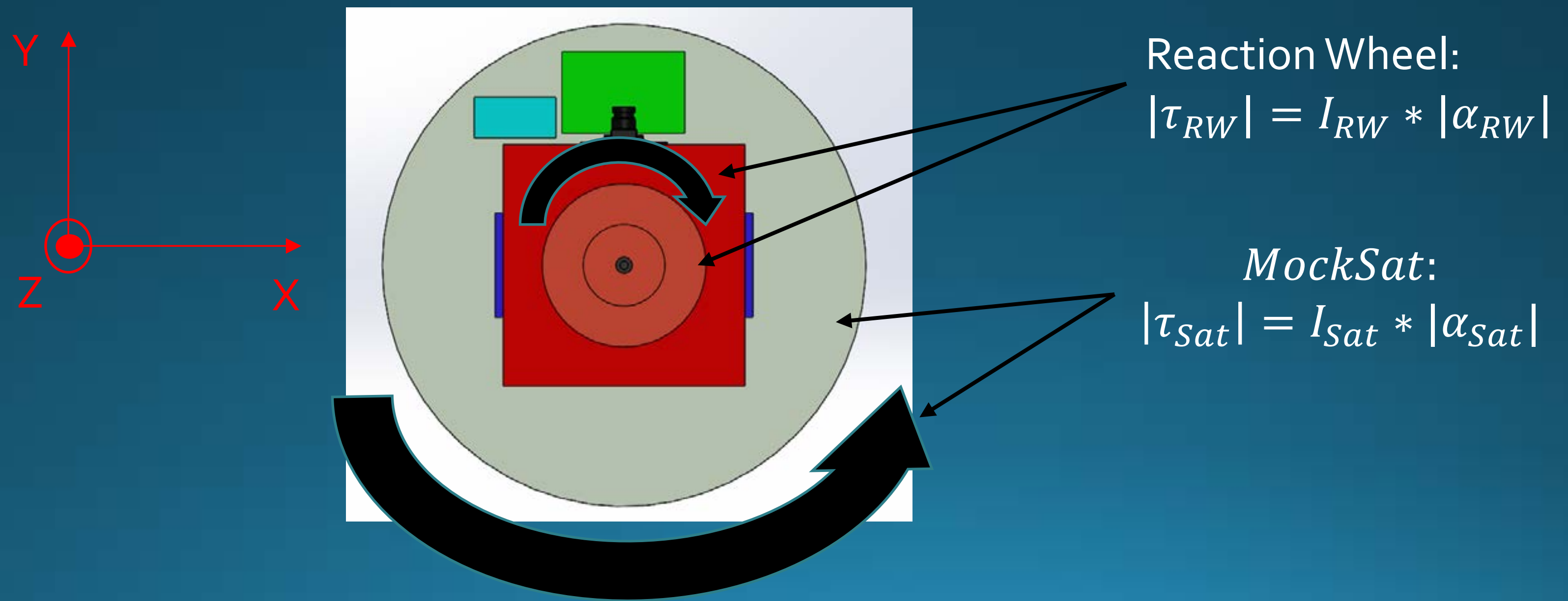
In addition to meeting the resolution requirements, the PIXY features onboard image processing at a rate of 50 FPS. It relays the location and size of detected objects over a range of output types, allowing it work with any chosen processor, while staying well above the bandwidth requirements.

ADCS: Actuators

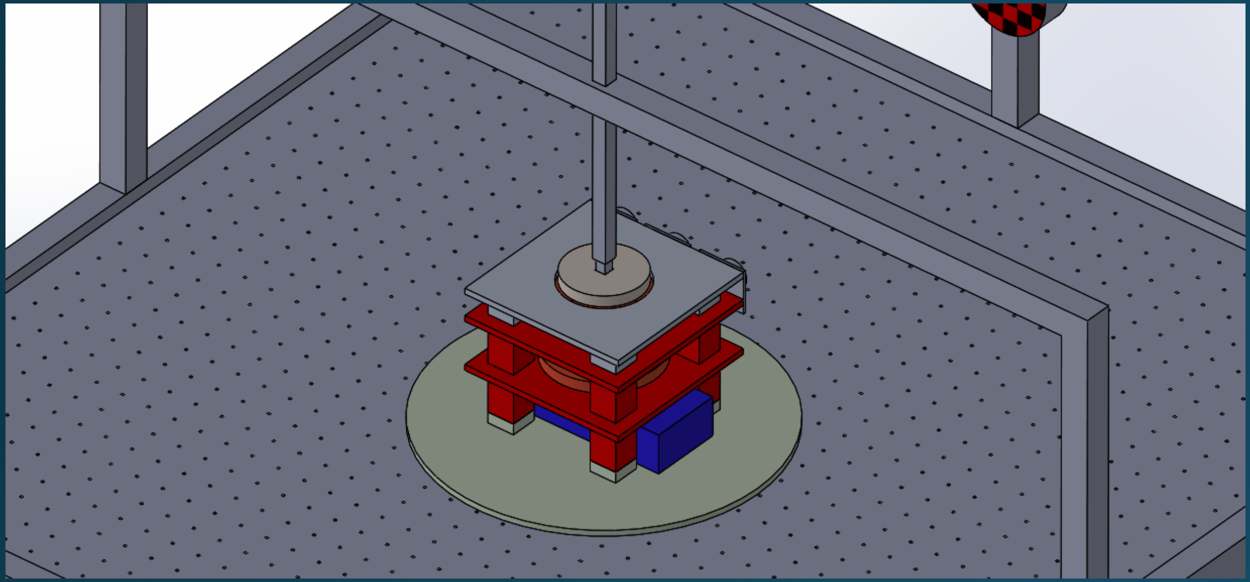
- Assume that torque imparted on reaction wheel is matched by equal and opposite torque on MockSat

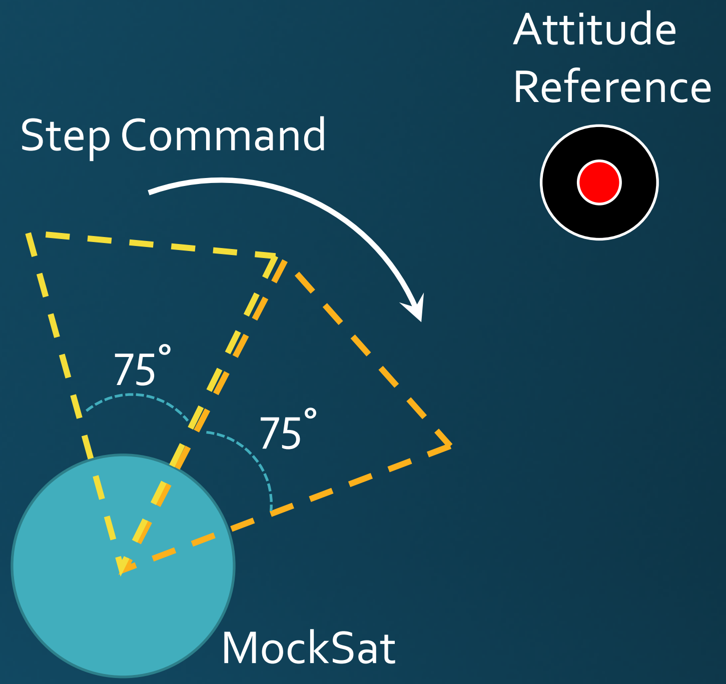
$$\Rightarrow |\tau_{RW}| = I_{RW} * |\alpha_{RW}| = I_{Sat} * |\alpha_{Sat}| = |\tau_{Sat}|$$

- Know approximate MOI of MockSat and maximum angular acceleration, gives maximum torque necessary for reaction wheel
  - Allows selection of motor based on torque requirements



ADCS: Actuators





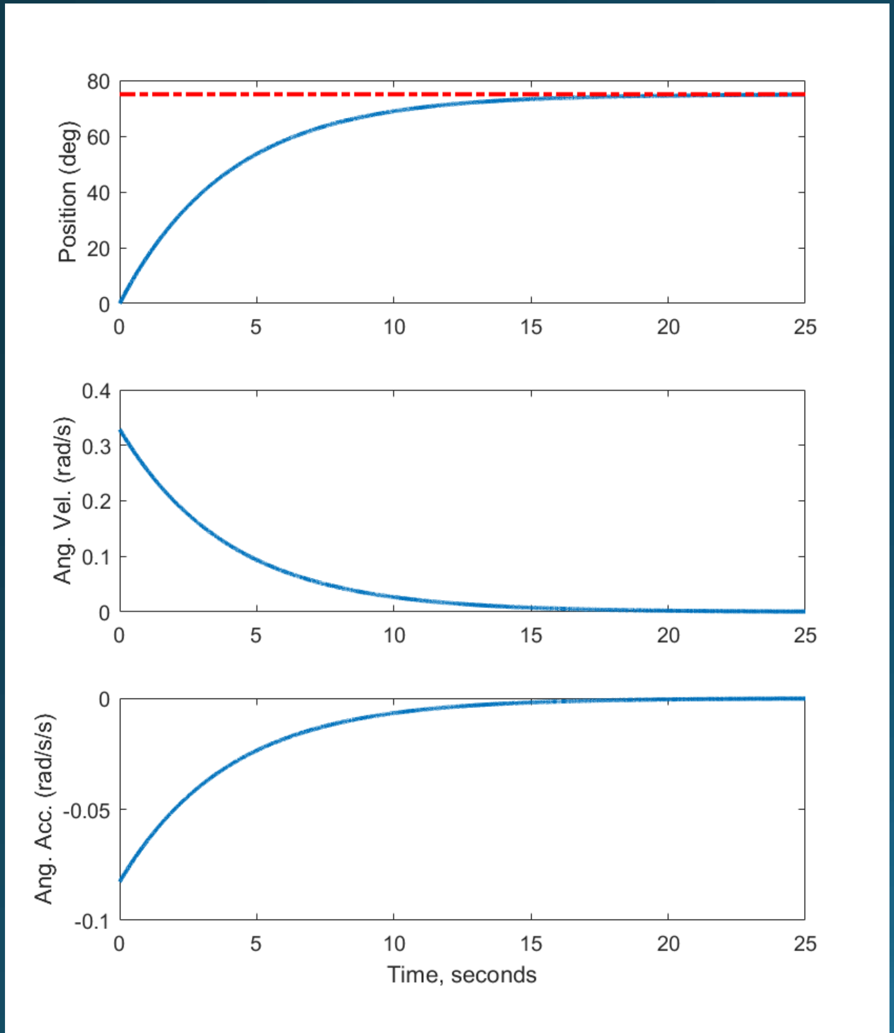
- Find max torque of MockSat based on pointing requirements
- Properties needed to solve:

$$\tau = Time\ Constant = \frac{1}{2\pi f_b} = \frac{1}{2\pi * .04} = 3.98\ seconds$$

- Approximate Moment of Inertia (MOI) from CAD model
- Step command angle of 75 degrees based off of coarse sensor FOV

ADCS: Actuators

- Find max torque of MockSat based on pointing requirements



$$\theta = A_o\left(1 - e^{-\frac{t}{\tau}}\right) \Rightarrow \theta'' = \alpha = -\frac{A_0}{\tau^2} * e^{-\frac{t}{\tau}}$$

- Step command: A_o = 75° = 1.31 radians
- Time constant: τ = 3.98 seconds
- MOI: I = 0.022 kg*m²
- Therefore α_{max} = 0.083 rad/s/s
- Max torque needed to rotate MockSat: τ_{mock}

$$\tau_{mock} = I * \alpha_{max} = 1.8 \text{ mNm}$$

ADCS: Actuators

Copyright: SKF

(1)

(2)

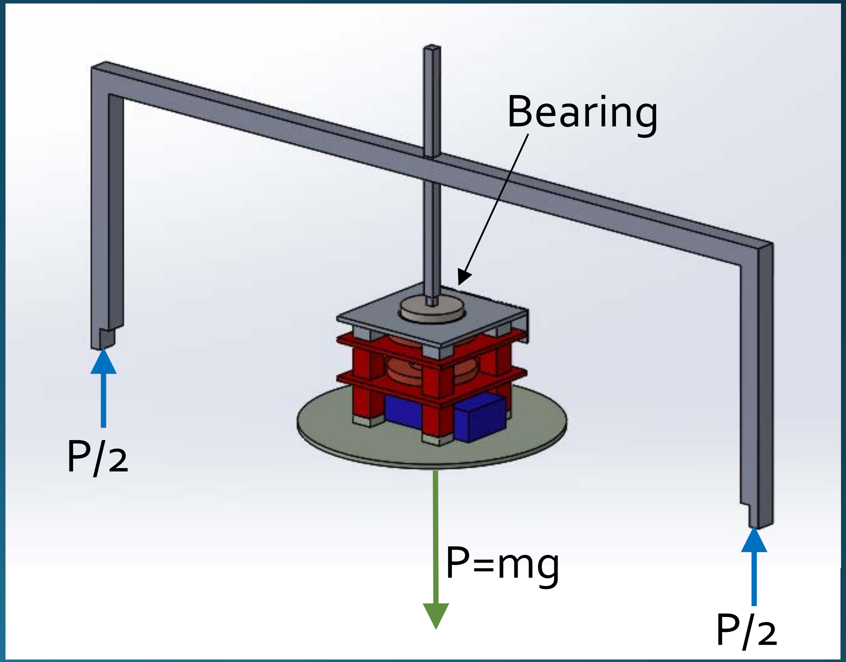
- Bearings with low Coefficients of Friction (COF)
  - Cylindrical roller bearing, COF ~0.0010 (1)
  - Self Aligning ball bearing, COF~0.0015 (2)
  - Can realistically achieve coefficient of friction < 0.002

- Need to show actuators can overcome internal bearing friction for worst case

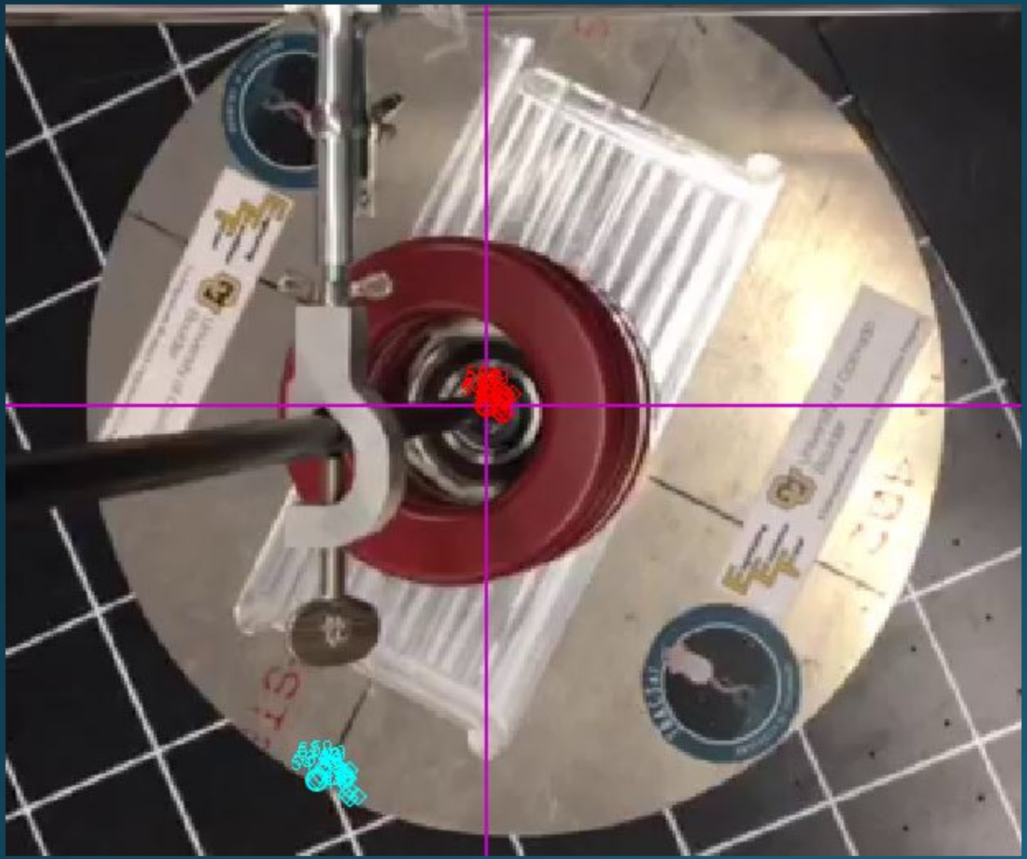
- τ_F : Torque needed to overcome friction of bearing

- $\tau_F = \frac{P * \mu * d_{inner}}{2} = \frac{5\text{ kg} * 9.81\frac{\text{m}}{\text{s}^2} * 0.002 * 0.0254\text{ m}}{2}$

$\tau_F = 1.2\,\text{mNm}$ ← Maximum possible torque to overcome for bearing



ADCS: Disturbance Torque

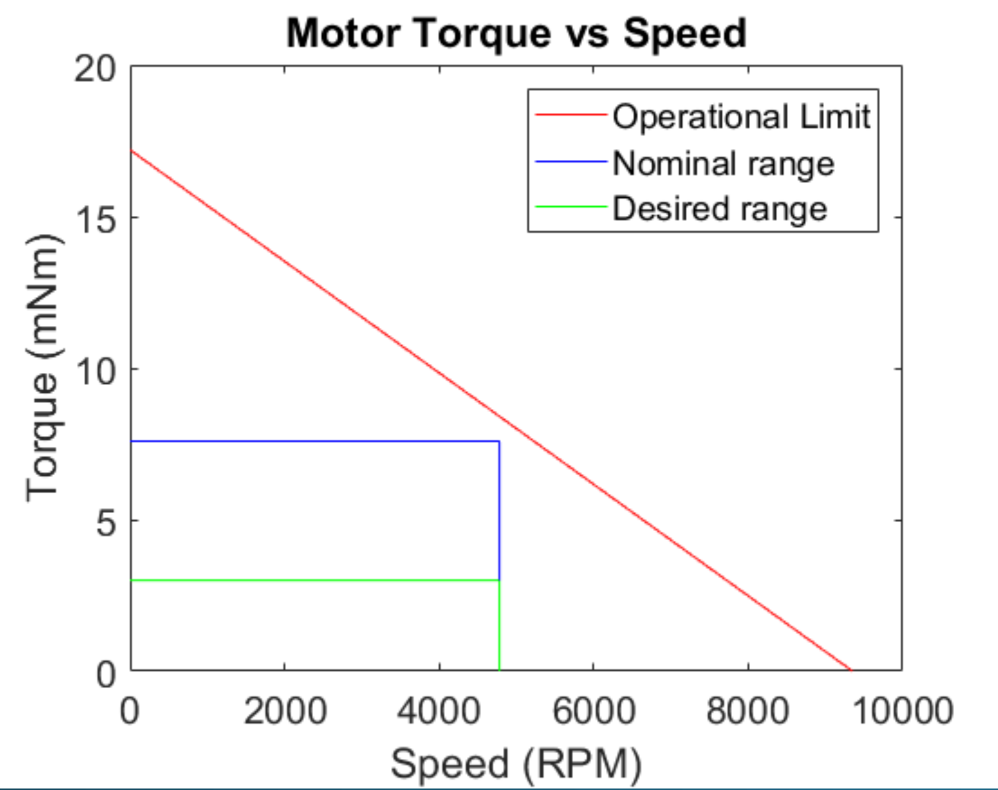


- Find maximum disturbance torque introduced by airflow between TestTable and MockSat
  - Maximum angular acceleration measured using Tracker Video Analysis
  - I = 0.037 kg m^2
  - Average alpha = 0.0308 rad/s/s

$$\tau_{Disturbance} = 1.14 \text{ mNm}$$

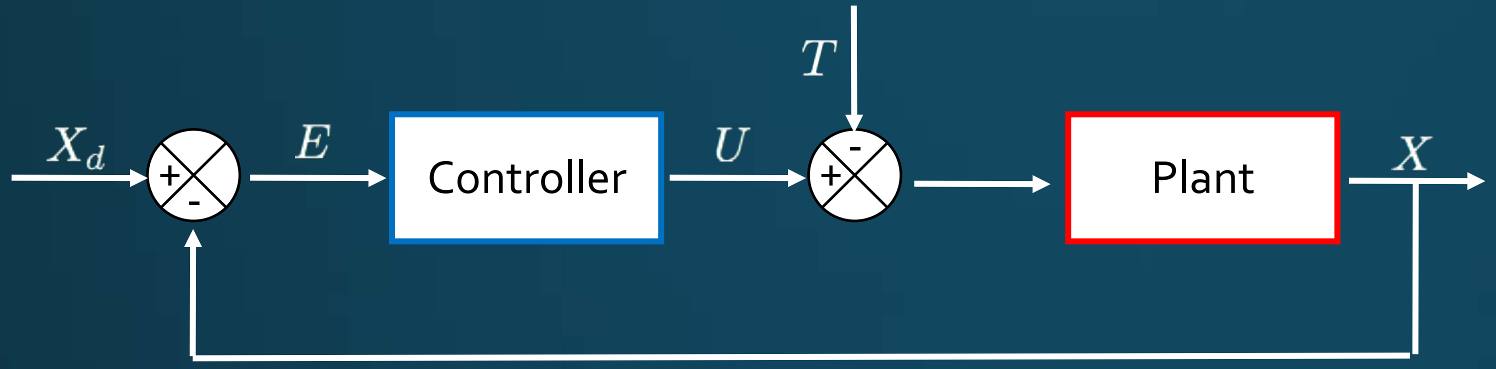
ADCS: Actuator Motor Requirements

Operational torque of motors under selection



- The maximum upper bound torque needed for the worst case in the Station Keeping design required by motor:
- $\tau_{max} = \tau_F + \tau_{Mock} + \tau_{Disturbance}$
- $\tau_{max} = 1.2 \text{ mNm} + 1.8 \text{ mNm} + 1.14 \text{ mNm}$
- $\tau_{max} = 4.14 \text{ mNm}$ ← Max torque needed by motor
- Rated continuous torque is: 7.59 mNm
- Overcoming torques from bearing friction, disturbances, and torque needed to rotate MockSat is **feasible**

ADCS: Controls



Governing Equation of Plant Dynamics:

$$\boldsymbol{I}\ddot{\boldsymbol{\theta}} + \dot{\boldsymbol{\theta}} \times (\boldsymbol{I}\dot{\boldsymbol{\theta}}) = \boldsymbol{M}$$

Simplifies in 1D:

$$I\ddot{\theta} = M$$

$$I\ddot{\theta} = M_{rw}(t) - \tau(t) \qquad M_{rw} \equiv u(t)$$

$$\boxed{I\ddot{\theta} = u(t) - \tau(t)}$$

θ	MockSat pointing angle
I	MockSat inertia
M	Net torque on the MockSat
M_{rw}	Control torque of reaction wheel
τ	Disturbance torques

ADCS: Controls

Assuming PD Control:

Not Feasible

$$I\ddot{\theta} + K_d\dot{\theta} + K_p\theta = K_p\theta_c - \tau(t)$$

$$\boxed{\Theta(s) = \frac{K_p}{s^2 I + K_d s + K_p}\Theta_c(s) - \frac{1}{s^2 I + K_d s + K_p}T(s)}$$

Steady State

$$\rightarrow \Theta(0) = \Theta_c(0) - \underbrace{\frac{1}{K_p}T(0)}_{\text{Steady State Error}}$$

PID Control: (integral control eliminates steady state error)

Feasible

$$I\ddot{\theta} + K_d\dot{\theta} + K_p\theta + \int_0^t \theta(t')dt' = K_p\theta_c - \tau(t)$$

$$\boxed{\Theta(s) = \frac{K_p}{s^2 I + K_d s + K_p + \frac{K_i}{s}}\Theta_c(s) - \frac{1}{s^2 I + K_d s + K_p + \frac{K_i}{s}}T(s)}$$

Summary: Feasibility

Functional Requirements	Feasibility Shown	Next Steps
1. The TestTable shall provide for 3DOF dynamics in a reduced-friction environment.	Air Table	Evaluate TracSAT air table, determine if it can be used.
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%.	ADCS Control	Begin structural design process.
3. The MockSat shall have the ability to maintain a controlled attitude relative to a point of reference within ±2.5°.	ADCS Sensors and Actuators	Evaluate programming and integration of sensors, determine exact size of reaction wheel
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).	Fault Injection	Model full control dynamics with fault injection. Characterize reaction wheel friction. Determine size of sensor bias.
5. The MockSat flight control software shall recover from 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) by regaining normal operation.	Fault Management	Model full control dynamics with fault management. Examine reaction wheel switching procedure.

Summary: Finance Budget

EXPENSE BUDGET

LLAMAS

Expense	Category	Expense Amount	Budget Remaining	Margin (%)
			$ 5,000.00	100%
Atmel SAM E70	Microcontroller	$ 50.00	$ 4,950.00	100%
Battery	Power	$ 90.00	$ 4,860.00	98%
Bearings	Structure	$ 50.00	$ 4,810.00	97%
Materials	Structure	$ 500.00	$ 4,310.00	87%
Mems Gyro	Sensors	$ 20.00	$ 4,290.00	87%
Motor Controller	Actuators	$ 100.00	$ 4,190.00	85%
Motors	Actuators	$ 1,000.00	$ 3,190.00	64%
Pixy	Sensors	$ 210.00	$ 2,980.00	60%
Power Regulator	Power	$ 200.00	$ 2,780.00	56%
Reaction Wheel	Actuators	$ 60.00	$ 2,720.00	55%
Reference Source	Structure	$ 60.00	$ 2,660.00	54%
Wiring	Power	$ 150.00	$ 2,510.00	51%
Xbee	Communication	$ 20.00	$ 2,490.00	50%
Totals		$ 2,510.00	$ 2,490.00	50%

Remaining Budget:
$2510.00

Margin:
50%

Summary: Mass Budget

Total MockSat Mass Budget			
Subsystem	Component	Quantity	Estimated Mass (g)
Structure	Base	1	1100
	Reaction Wheel Mounts	2	520
	Bearing Mount	1	480
ADCS	Reaction Wheel Disks	2	200
	Motors	2	50
	Fine Sensors	1	50
	Coarse Sensors	1	50
	IMU	1	50
	Processor(s)	2	50
	Motor Controllers	2	50
EPS	Batteries	1	1000
Misc	Wires	1	100
	Bearing	1	300

Total Estimated Mass: 4870 g

Summary: Power Budget

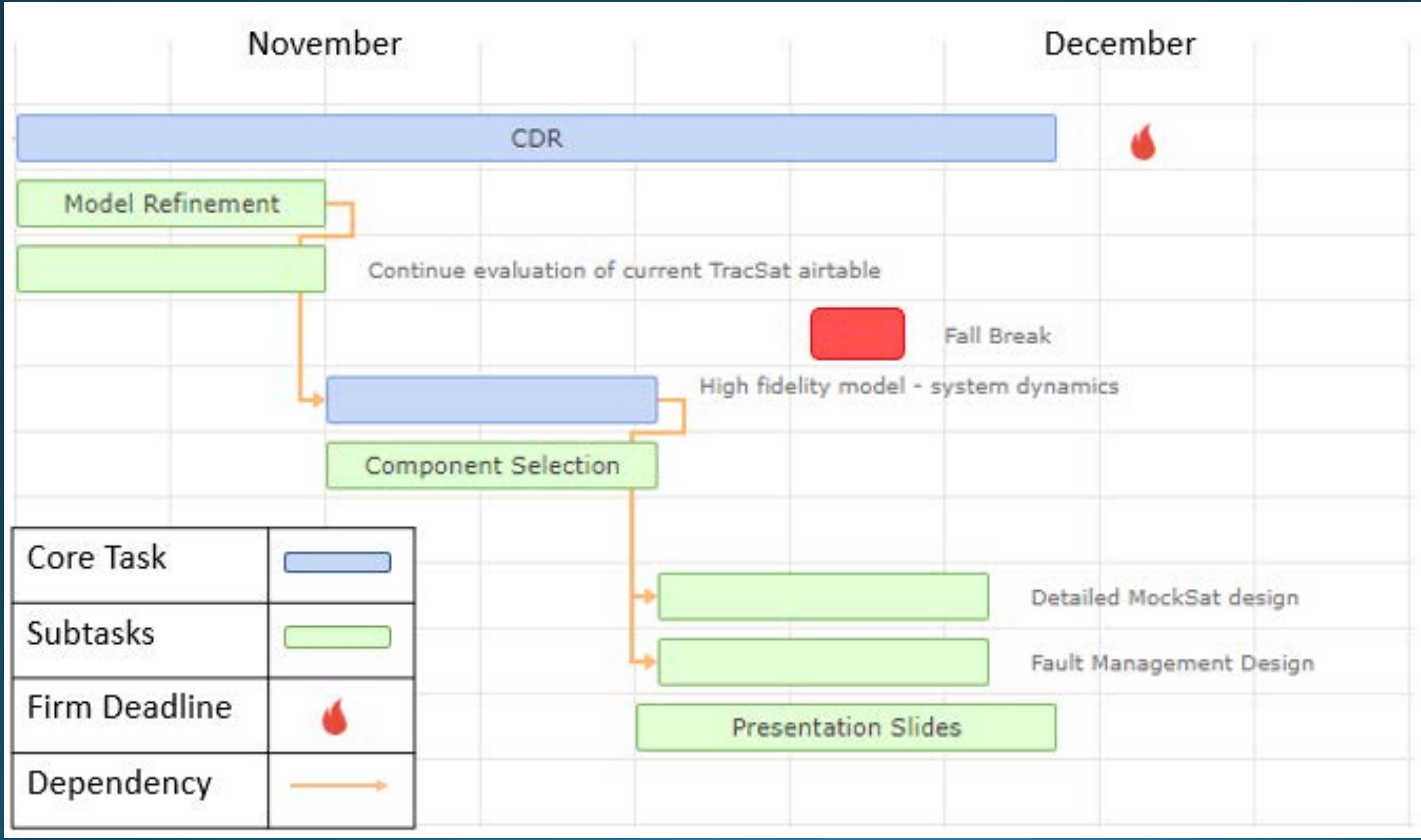
MockSat Power Budget			
Component	**Power Draw (W)**	**Voltage Rating (V)**	**Current Draw (A)**
Motor	5	24	0.208
Micro-Controller (Atmel SAM E70)	0.54	3.6	0.15
Xbee Comm System	0.432	3.6	0.12
Pixy Camera (3)	1.4	10	0.14
MEMS Gyro	0.018	5	0.0036
Total			0.902

- This results in a maximum current draw of 0.902 A
- Accounting for losses and margin, a 2 Ah battery can be used
- It is easy and inexpensive to find a battery of this size

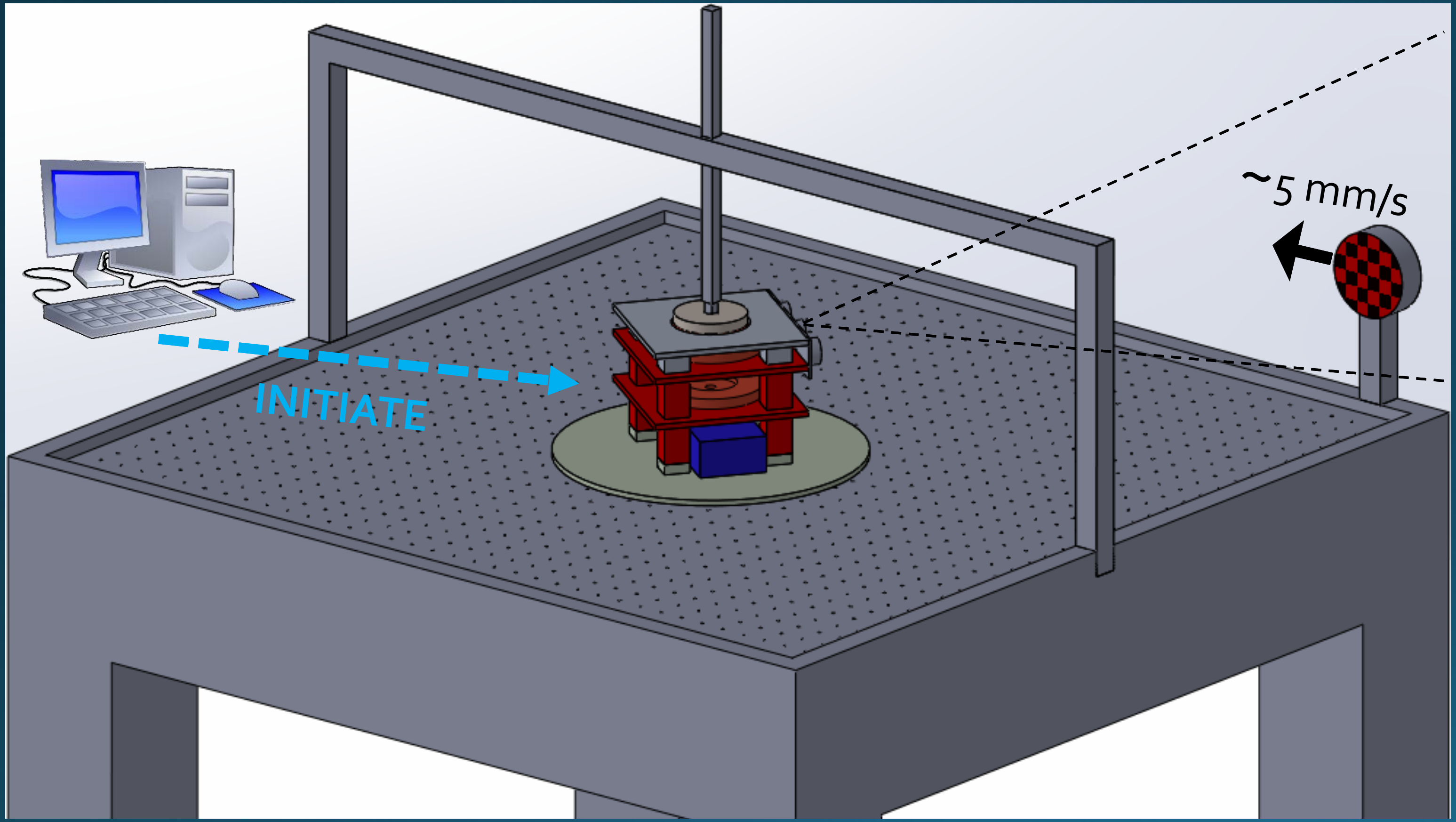
1.0	Project Overview, CONOPS, & FBD	*Kristyn S., Zach R.*
2.0	Baseline Design	
2.1–	TestTable	*Andrew M.*
2.2–	MockSat	*Andrew M.*
2.3–	Fault Injection and Management	*Corwin S.*
3.0	Critical Project Elements (CPEs)	
3.1 –	Fault Management and Injection System	
3.1.1	Reaction Wheel Fault	*Corwin S.*
3.1.2	Sensor Faults	*Pol S.*
3.2–	ADCS	
3.2.1	Sensors	*Dalton A.*
3.2.2	Actuators	*Zach R.*
3.2.3	Controls	*Dalton A.*
4.0	Status Summary, Plan of Action	*Kristyn S.*
5.0	Q & A	*LLAMAS*

Backup Slides

Schedule


November
December
CDR
Model Refinement
Continue evaluation of current TracSat airtable
Fall Break
High fidelity model - system dynamics
Component Selection
Detailed MockSat design
Fault Management Design
Presentation Slides
Core Task
Subtasks
Firm Deadline
Dependency

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

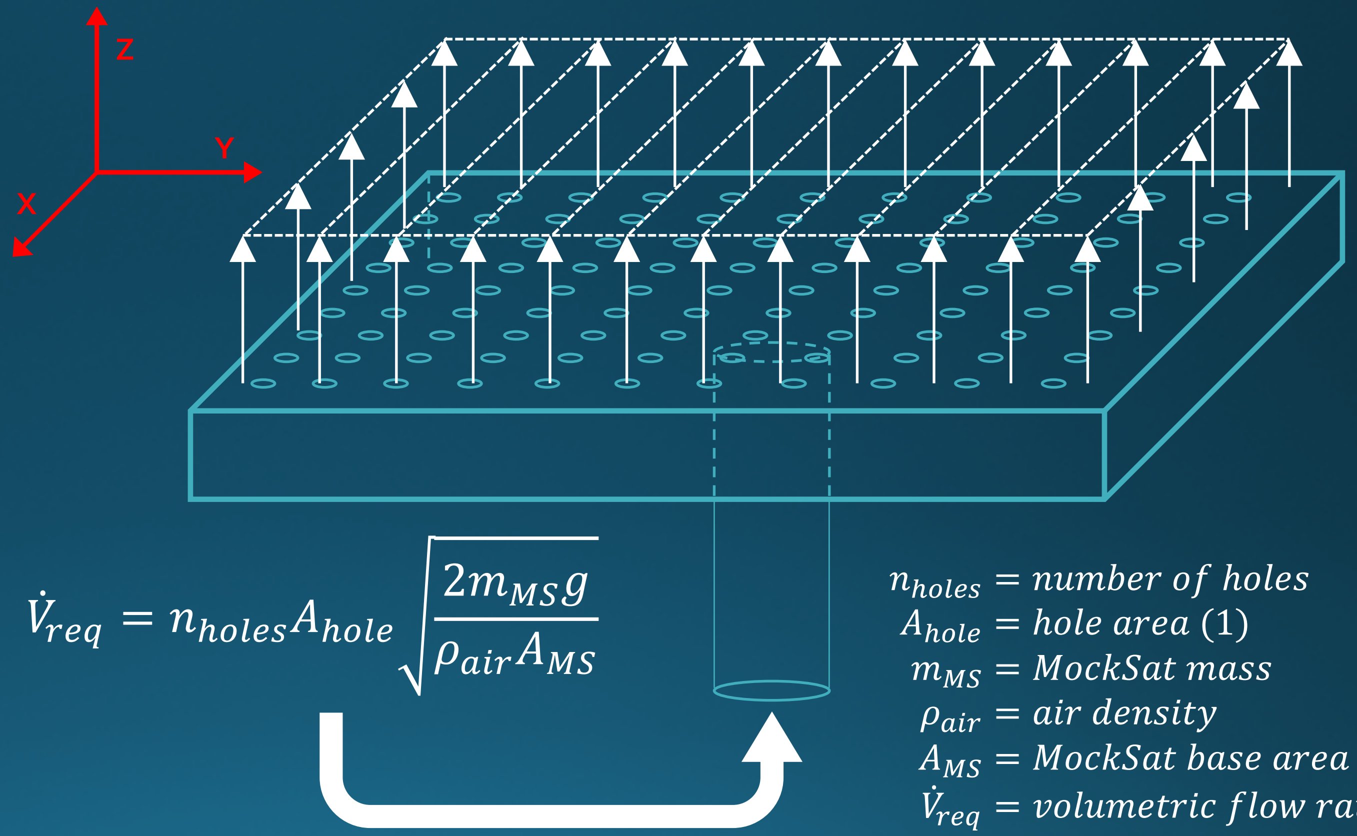
$$v_{target} \approx 5\ \frac{mm}{s}$$

Baseline Design – TestTable

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

<u>Air table:</u>

- 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].



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

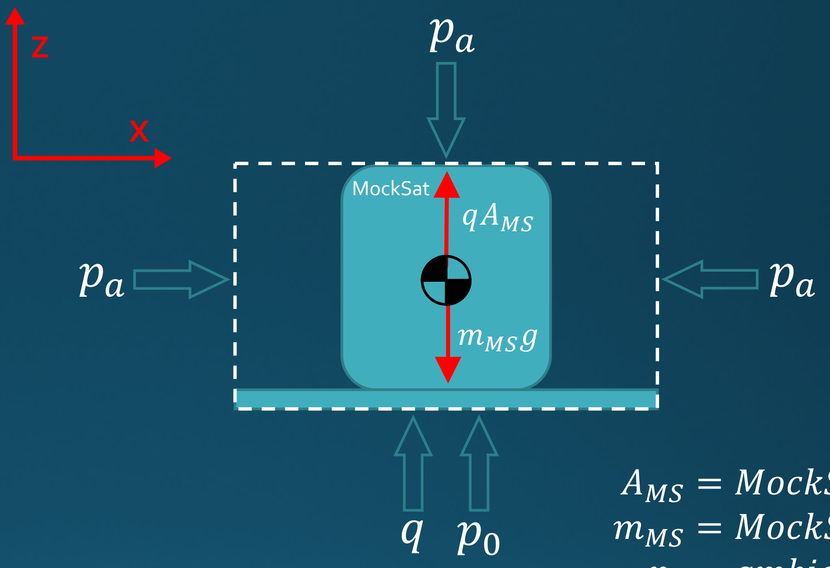
n_{holes} = number of holes
A_{hole} = hole area (1)
m_{MS} = MockSat mass
ρ_{air} = air density
A_{MS} = MockSat base area
$\dot{V}_{req}$ = volumetric flow rate

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

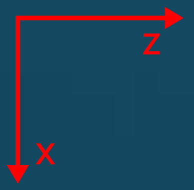
$$\sum F_x = (p_0 - p_0)A_x = 0$$

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

$$\sum F_z = (\not{p_0} + q - \not{p_0})A_z = qA_z = mg$$

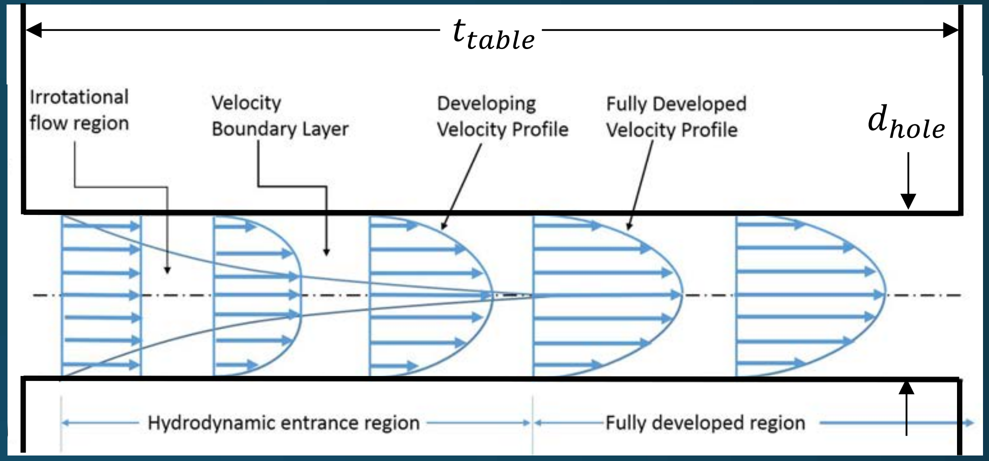
Baseline Design – TestTable

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



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.

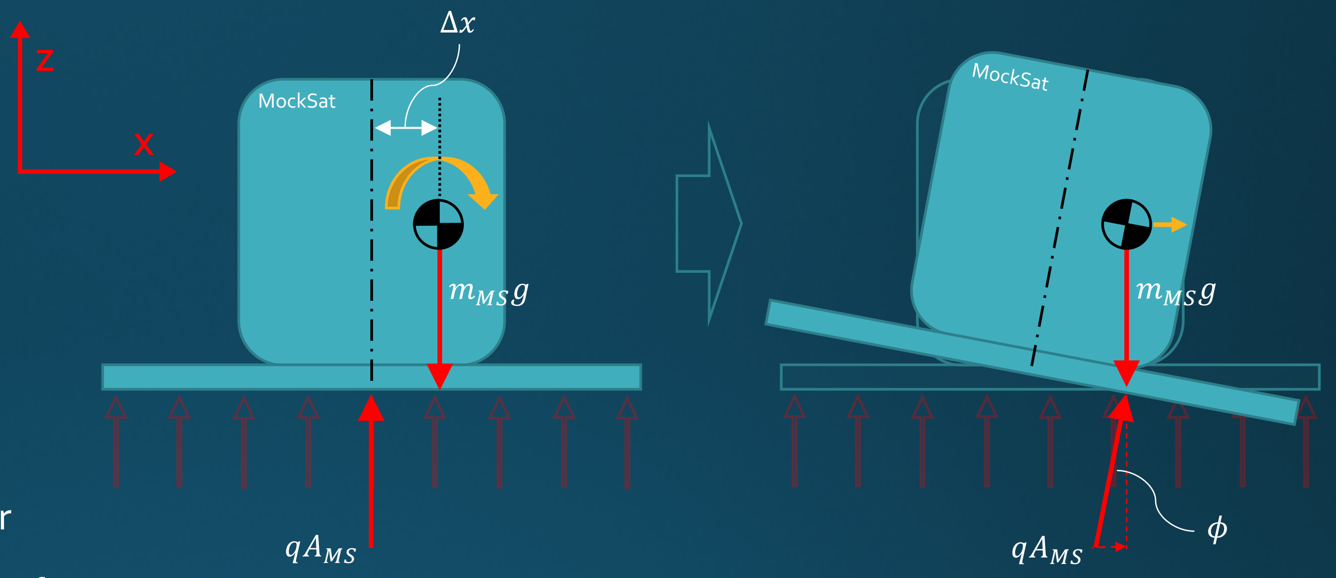


$$Re = \frac{\rho u L}{\mu} \rightarrow \frac{\rho_{air}\left(\sqrt{\frac{2m_{MS}g}{\rho_{air}A_{MS}}}\right)t_{table}}{\mu_{air}} \quad \text{for } t_{table} = \frac{1}{2}''$$

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

Baseline Design – TestTable

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



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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.*

Investigation of potential losses:

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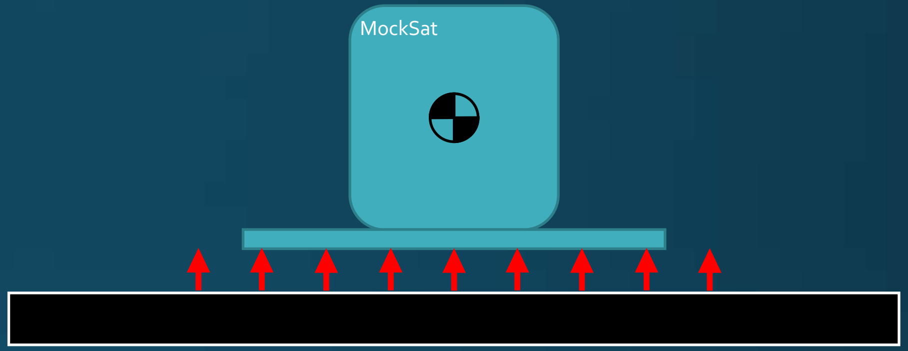
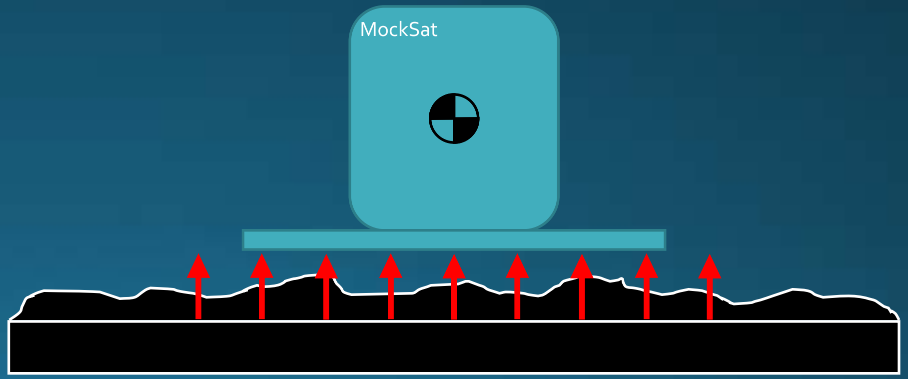
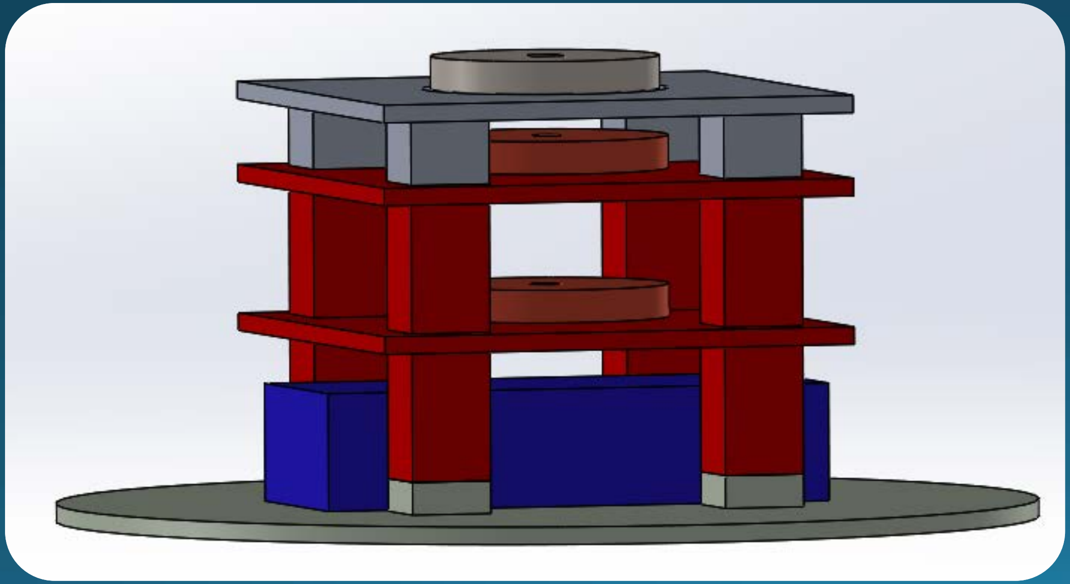




Current MockSat Structural Design

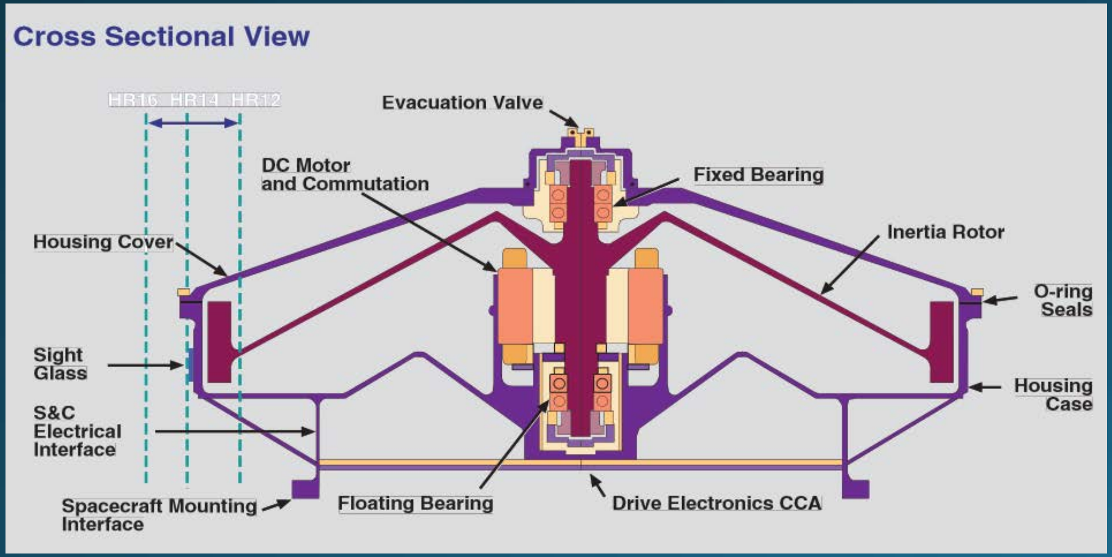
- Total Mass = 4.2194986 kilograms
- Moment of Inertia about axis of rotation = 0.0218676 kg*m^2
- Structure and Baseplate Material = AL 6061, density = 2.7 g/cm^3
- Reaction Wheel Material = Brass, density = 8.4 g/cm^3
- Bearing Material = Stainless Steel, density = 7.7 g/cm^3



Baseline Design – Fault Injection & Management System: Overview

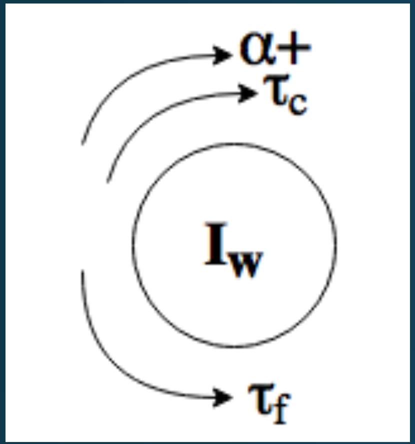
- In order to recover from faults, use redundant components to enable switching upon fault detection

Using two reaction wheels, one for redundancy to replicate Honeywell HR-18 reaction wheels



Using three digital imagers, one for redundancy to replicate Sodern HYDRA Star Tracker

CPE – Fault Injection and Management System: Actuators



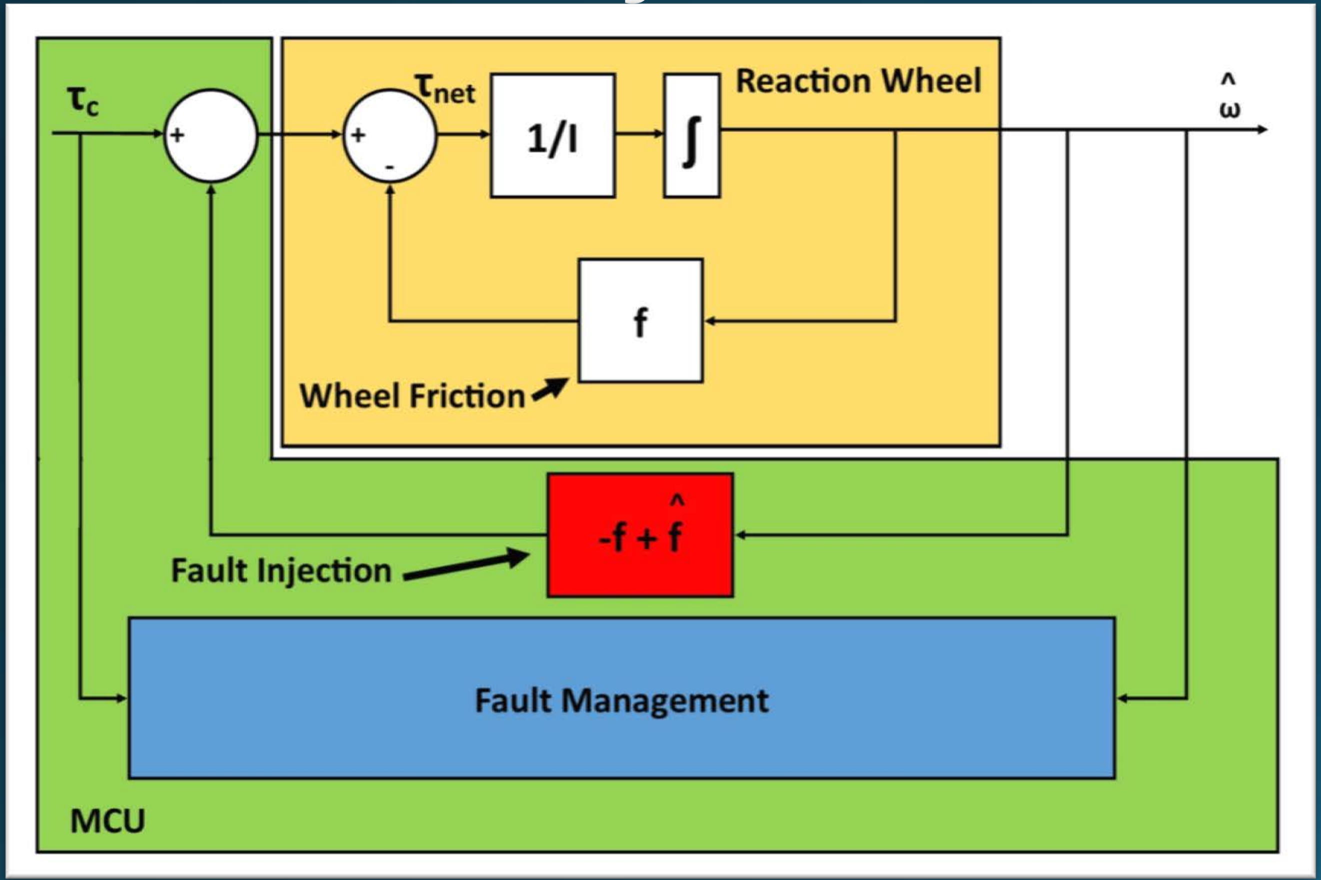
Reaction wheel dynamics

$$\tau_{net} = \text{Net torque on reaction wheel}$$
$$\tau_c = \text{Commanded torque}$$
$$\tau_f = \text{Torque due to friction, nominal}$$
$$I_\omega = \text{Reaction wheel moment of inertia}$$
$$\alpha_\omega = \text{Reaction wheel angular acceleration}$$

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

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

CPE – Fault Injection and Management System: Actuator Injection



FBD for induced reaction wheel friction

- Nominal reaction wheel dynamics:

$$\omega = \int \frac{1}{I}(\tau_c - f(\omega))$$

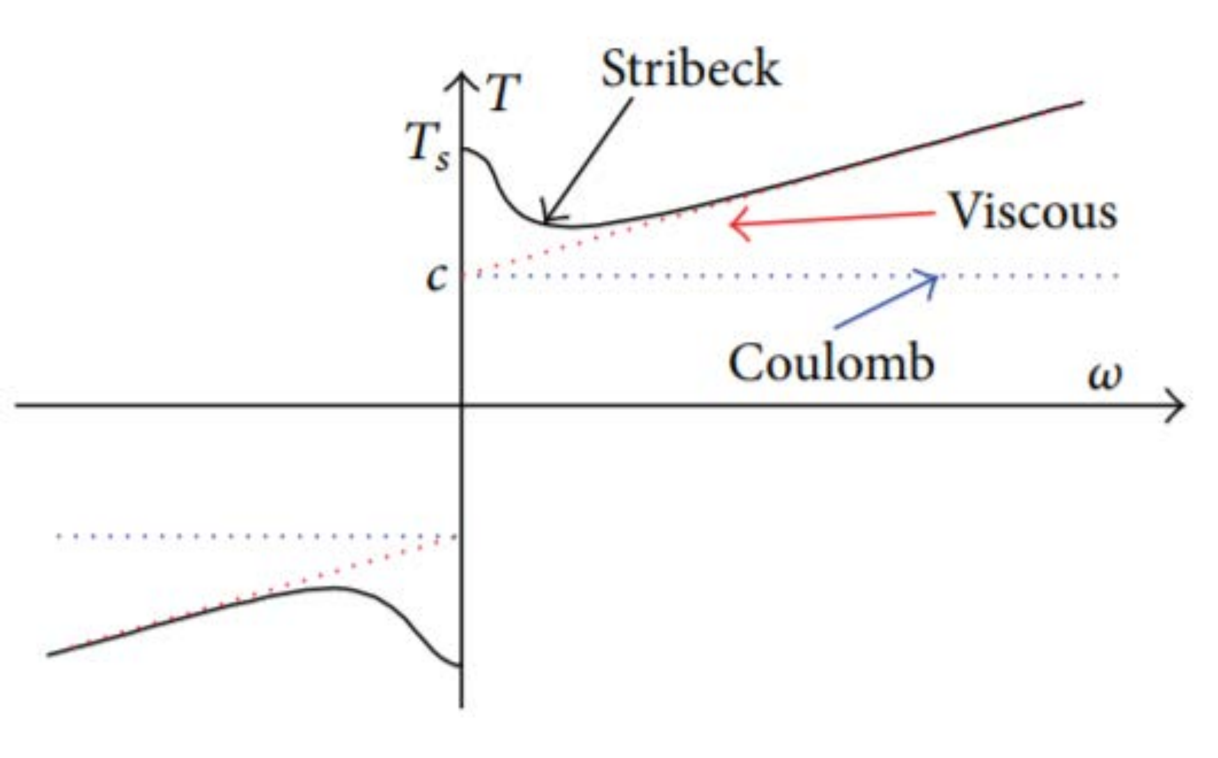
- With forcing function:

$$\hat{f}(\omega) = \text{Friction injection function}$$

$$\hat{\omega} = \int \frac{1}{I}(\tau_c - (-f(\omega) - \hat{f}(\omega)) - f(\omega))$$

- The modified wheel speed due to the fault injection will be read by the fault management system as if it is the actual actuation of the system in response to the commanded torque.

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



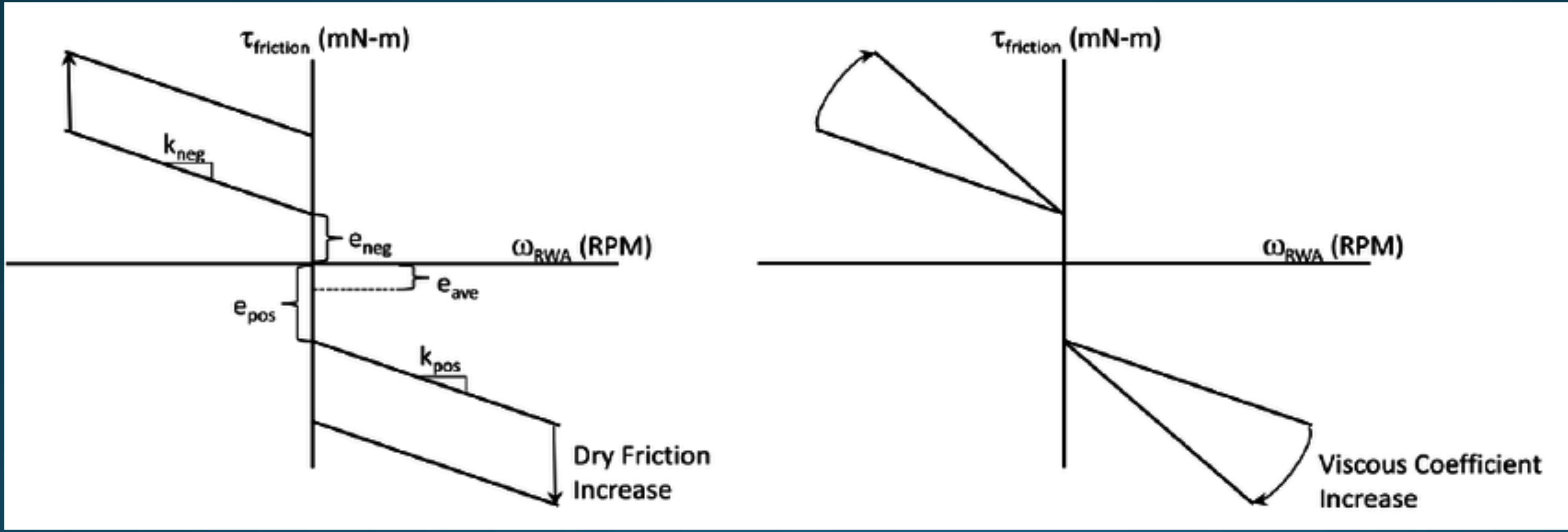
Representative friction torque curve of reaction wheel

- 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

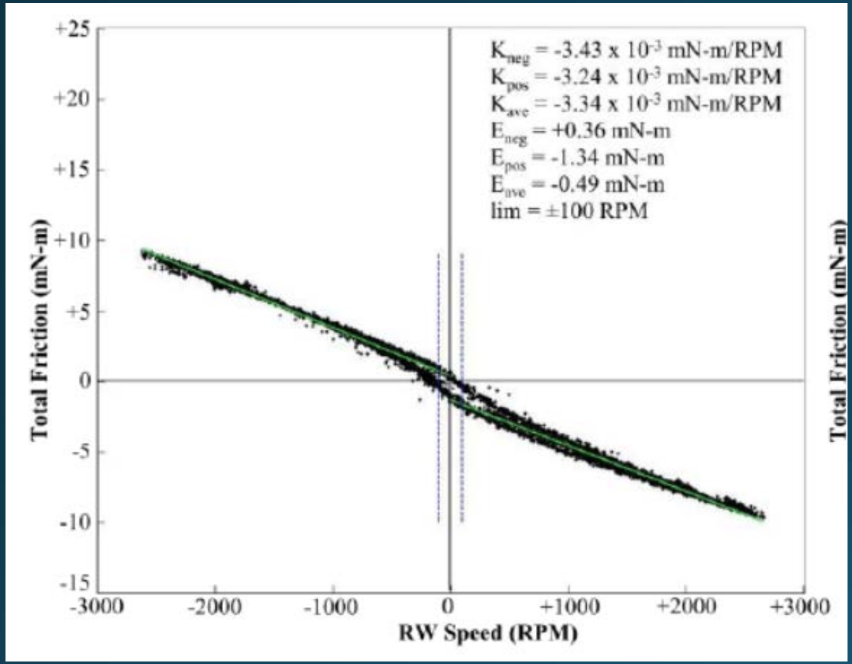
- Hard failures in reaction wheels are caused by an increase in Coulomb friction.

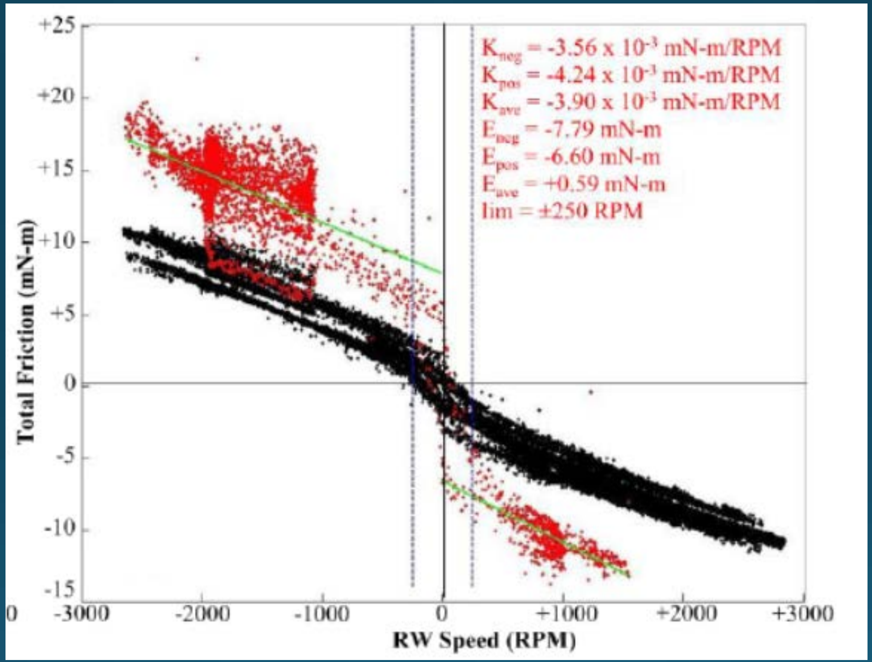


Left: Increase in Coulomb friction. Right: Increase in Viscous friction

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





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

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:

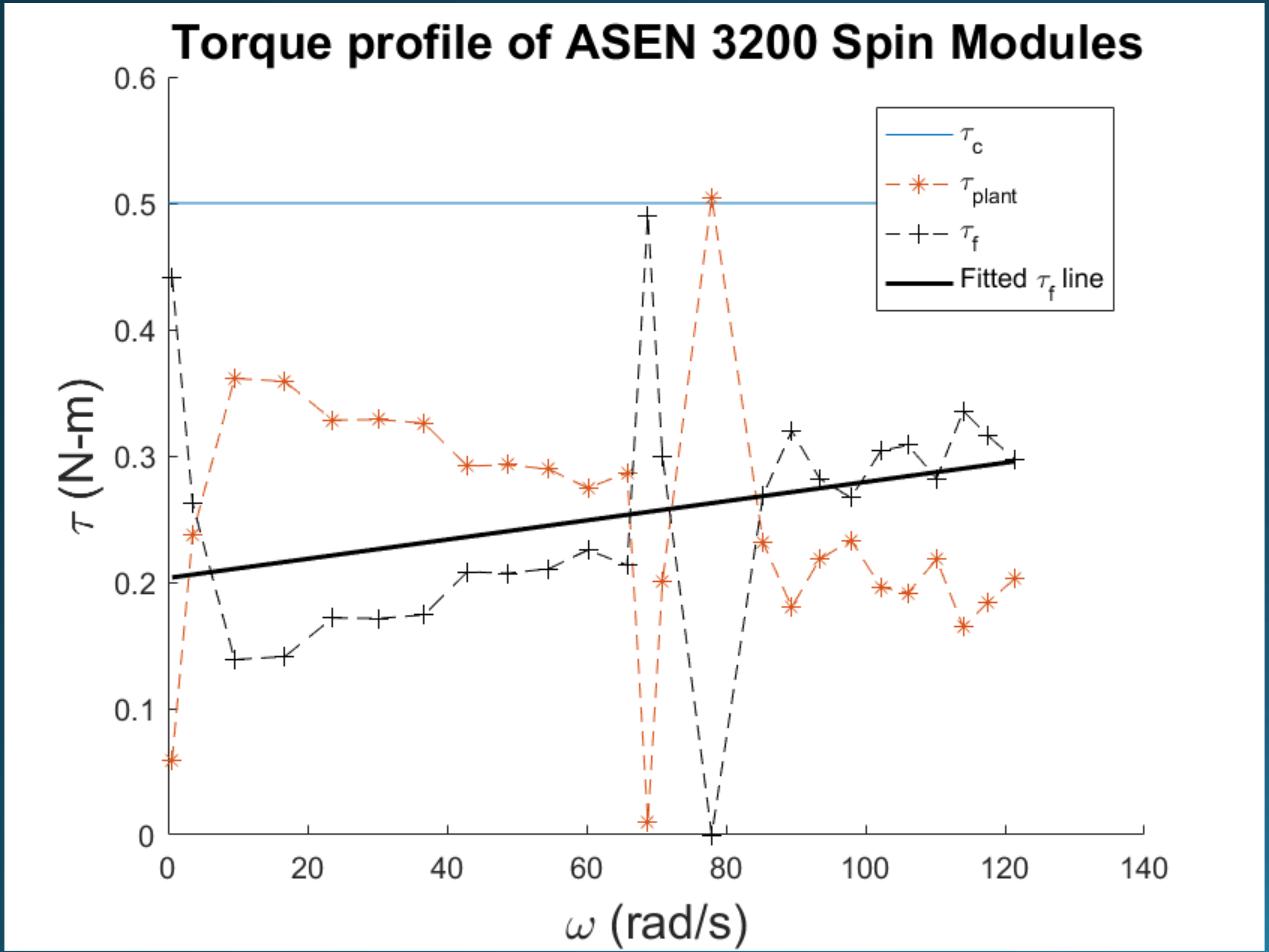
$$\hat{\alpha}_\omega = \frac{\Delta\omega}{\Delta t}$$

- 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

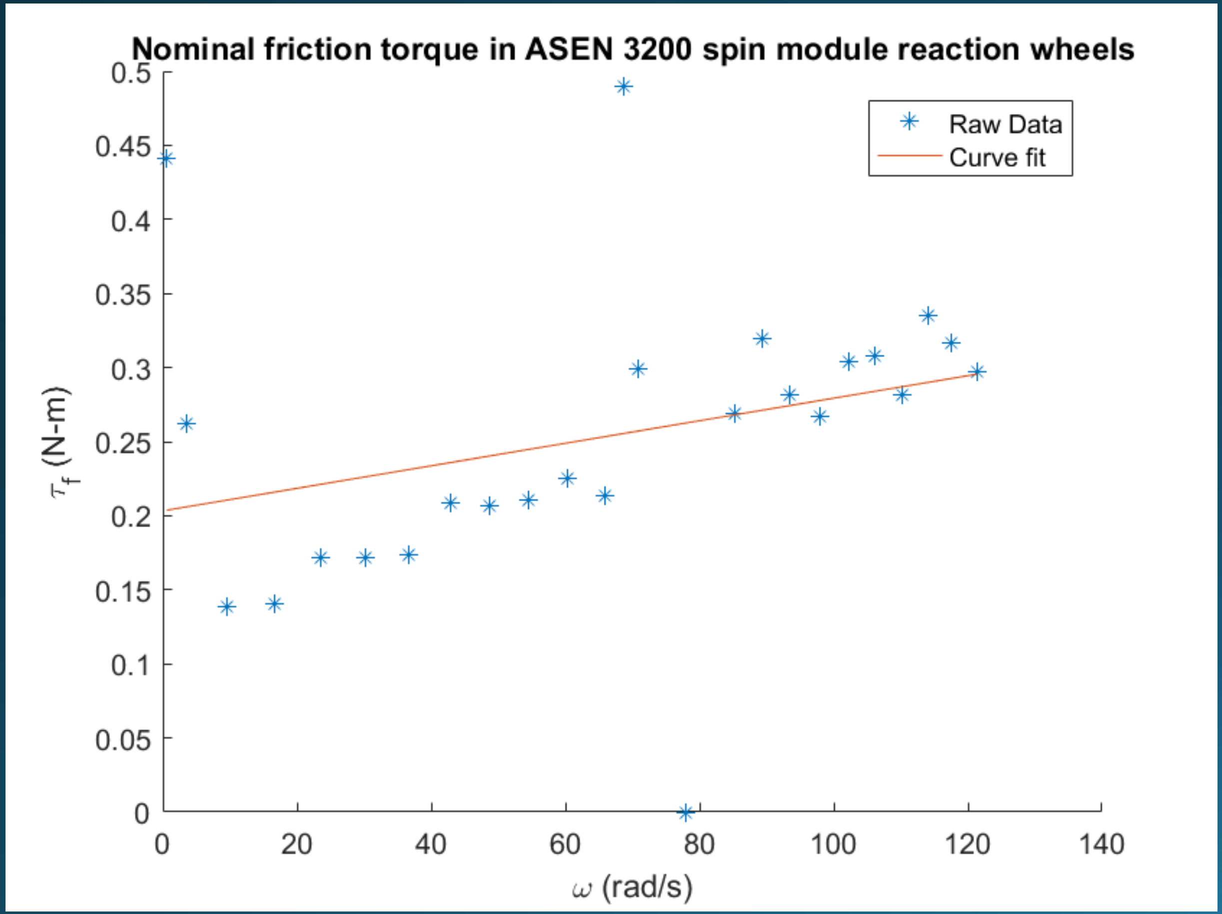
CPE – Fault Injection and Management System: Example Analyzing 3200 Reaction Wheels

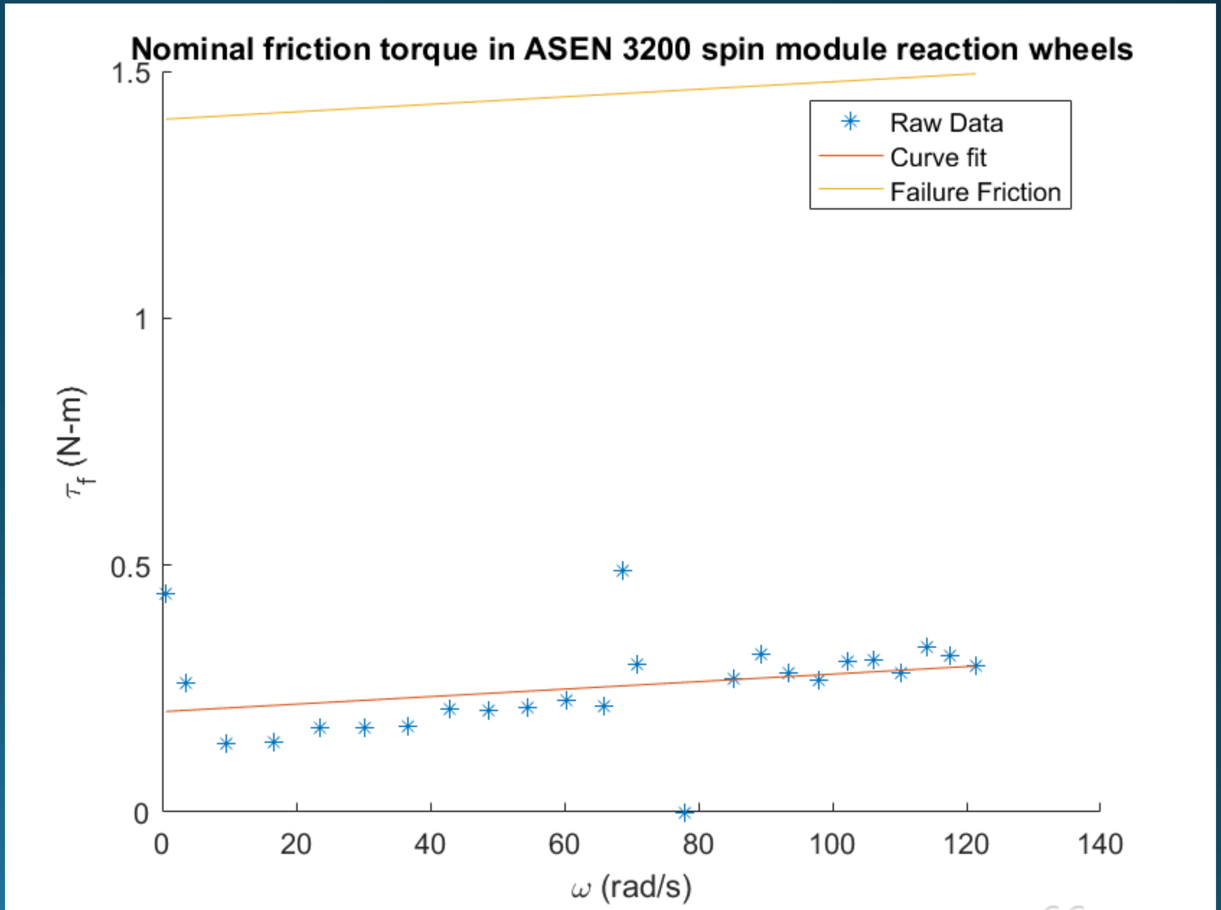


- Used data from ASEN 3200 to examine nominal friction in this system.
- Constant commanded torque of 0.5 N-m
- Data file contained time stamps every 0.1 s with commanded torque and wheel speed.
- From this data, the friction torque present as a function of angular velocity was calcucated.
- Then, a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

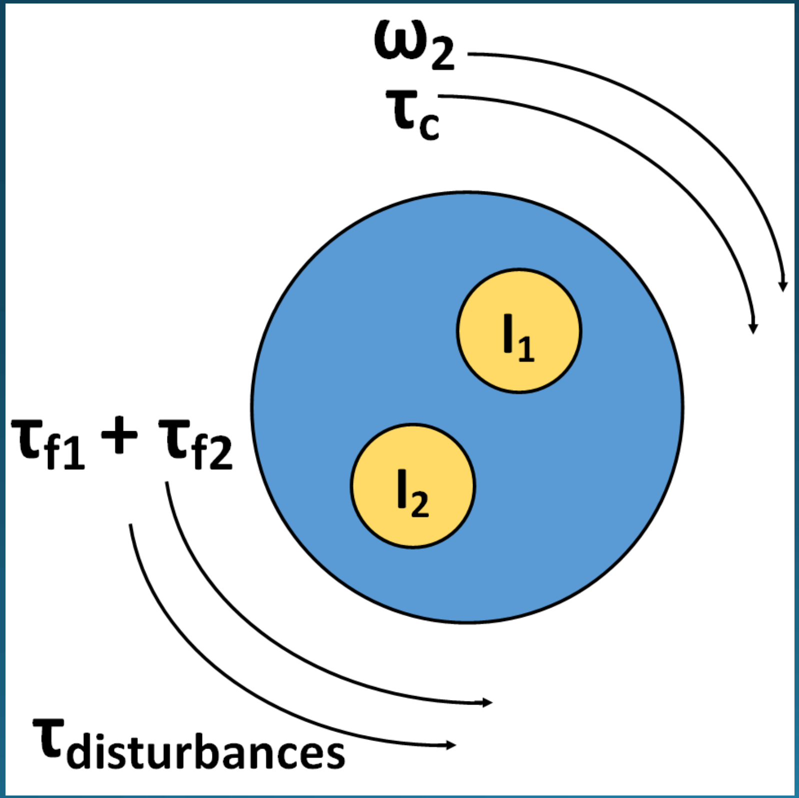
- Triggering a fault – Example using ASEN 3200 Spin Module data





CPE – Fault Injection and Management System: Actuators

- In order to switch from one reaction wheel to another, the frictional torque of reaction wheel 1 must be classified as it will be a disturbance torque in the system.
- Reaction wheel switch does not need to be bumpless. For the purpose of this project a longer recovery is sufficient.



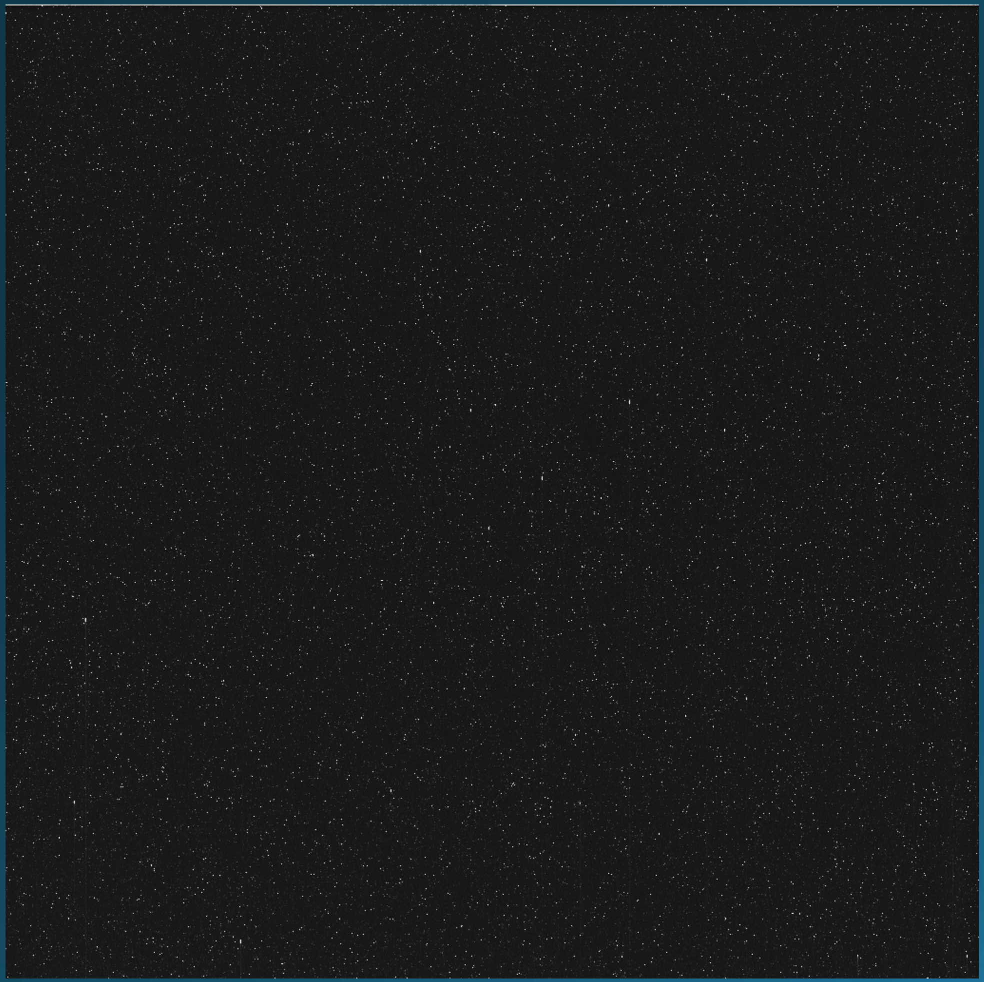
CPE – Fault Injection and Management System: Sensors

GOES-16 also uses redundant SSIRUs containing hemispherical resonator gyros (shown in the figure below), however in 16 million hours of use one has never failed. [2]

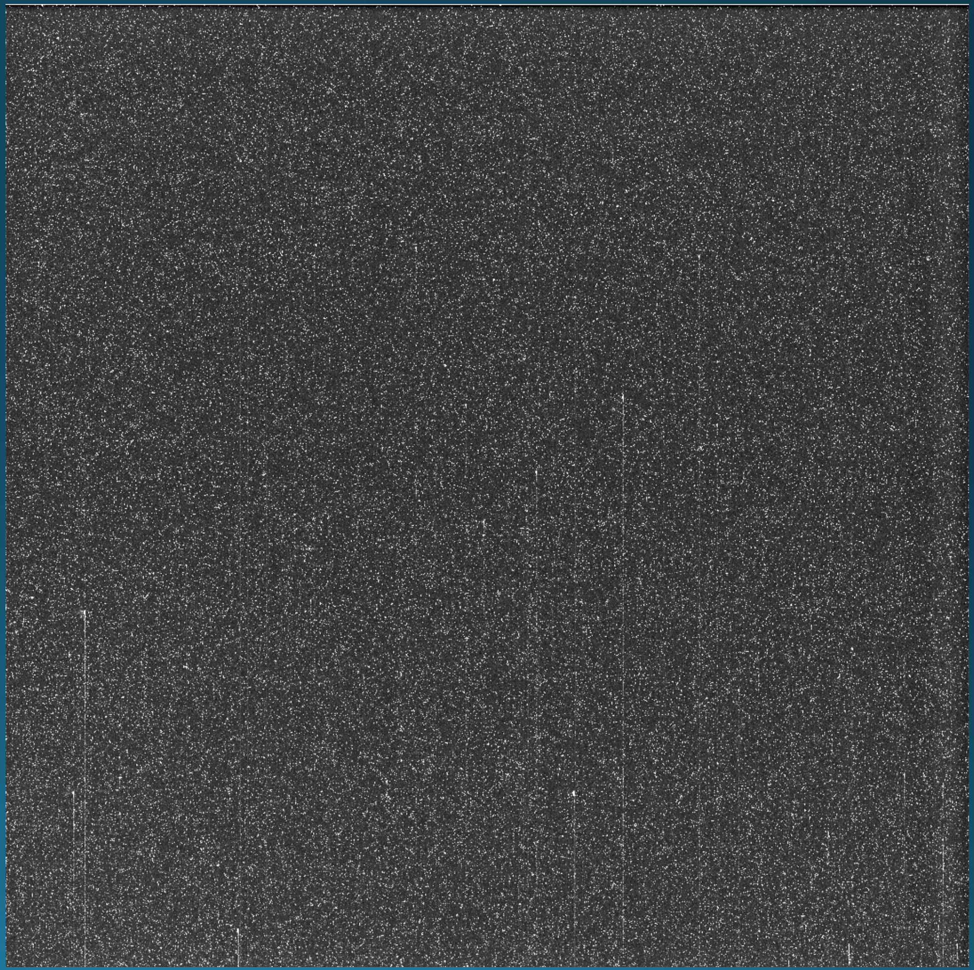
- "The three-head SODERN Hydra Star Tracker is used for attitude measurements, with two heads operating continuously and one serving as a cold spare." [1]
- Star measurements from the multiple heads are combined within the star tracker software to produce a “fused” attitude estimate from the 2 optical heads. [1]
- "Ground processing of the sequence telemetry simply compares the attitude based upon IMU gyro propagation to the attitude from the star tracker, and computes an estimate of the alignment errors from that data. Alignment corrections are then uplinked to the spacecraft." [1]

Fault Injection and Management System: Sensors

Subtle example of hot pixels

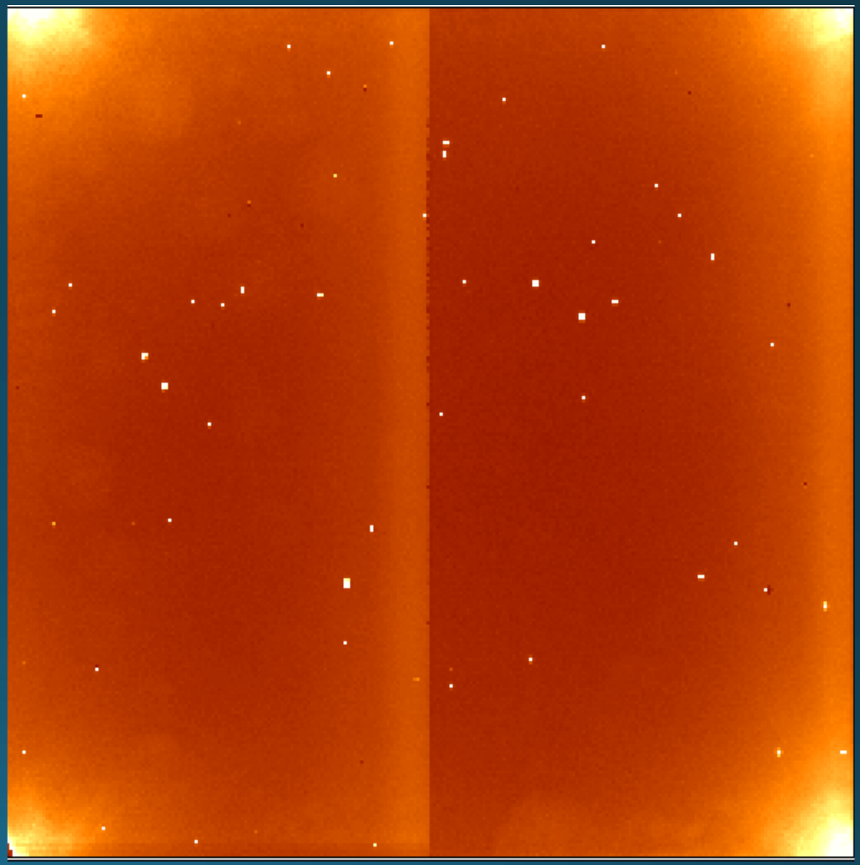


Extreme example of hot pixels



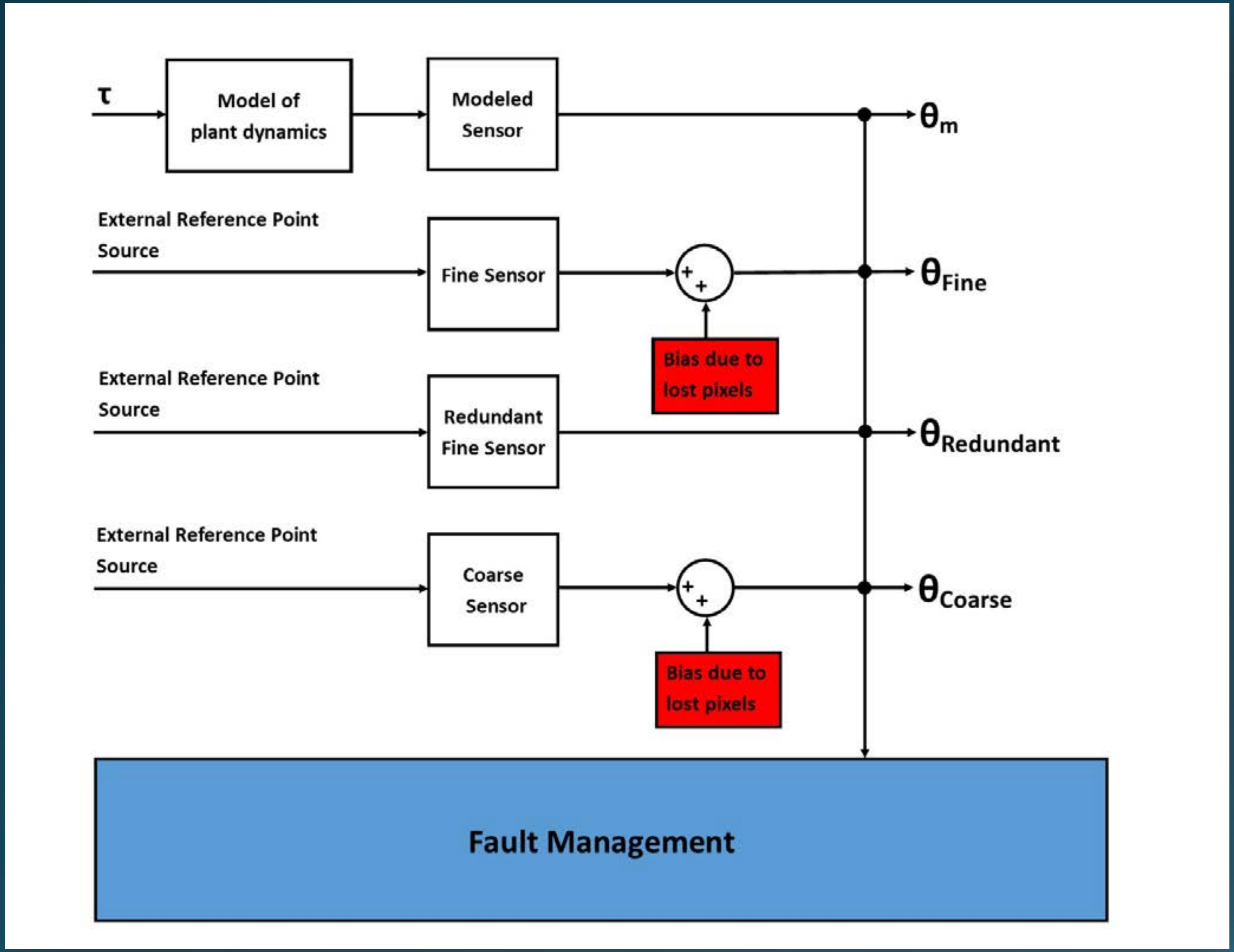
CPE – Fault Injection and Management System: Sensors

- "Hot pixels are pixels with excessive charge compared to the surrounding pixels." [3]
- Hot pixels show up when camera sensor gets hot during long exposure. [4]
- Energetic particles impact charged-coupled device producing hot pixels. [4]



Copyright: Space Science Telescope Institute

Fault Injection and Management System: Sensors



- Fault is recreated by manipulating output sensory data
- θ from model, fine sensor, and coarse sensor are compared
- From comparison, fault in fine sensor or coarse sensor is identified and classified
- Data from faulted sensor ignored and responsibilities shifted to redundant sensor

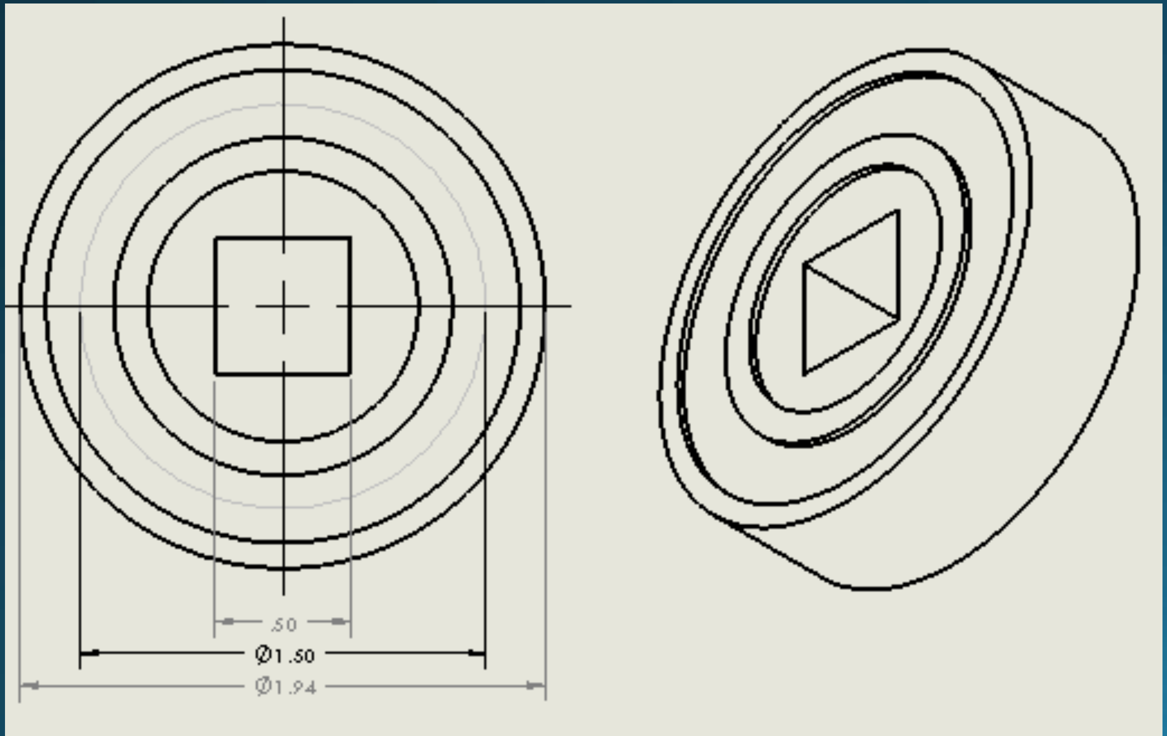
ADCS: Station Keeping

Functional Requirement 3:

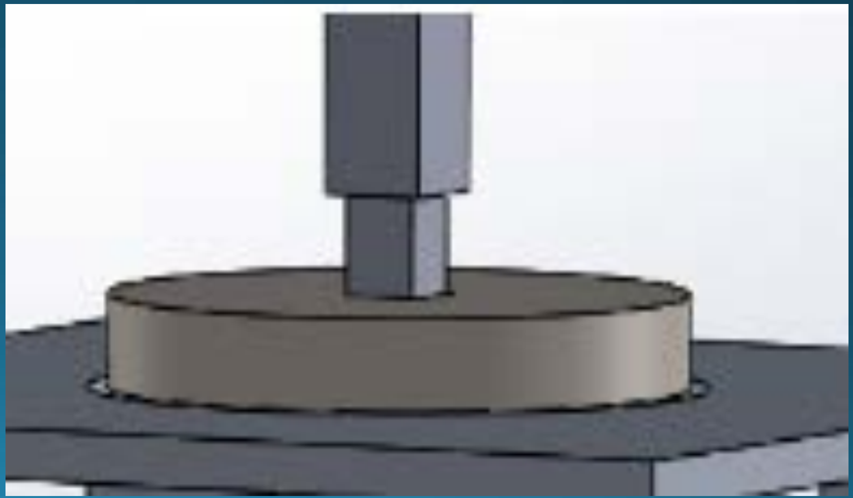
- *The MockSat shall have the ability to maintain a controlled attitude relative to a point of reference within ± 2.5 degrees*

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

Bearing design



Rod inserted into bearing

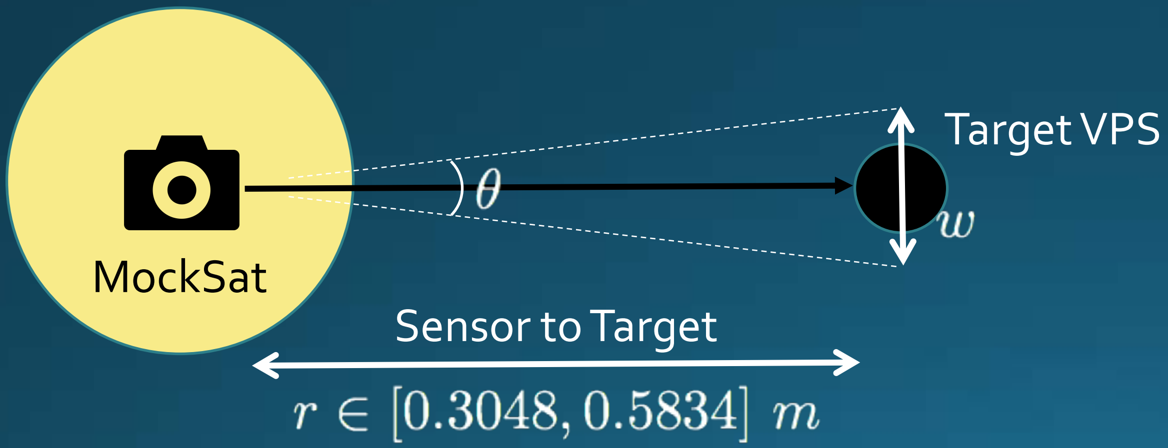


CPE – Fault Injection and Management System: Sensors

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

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

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

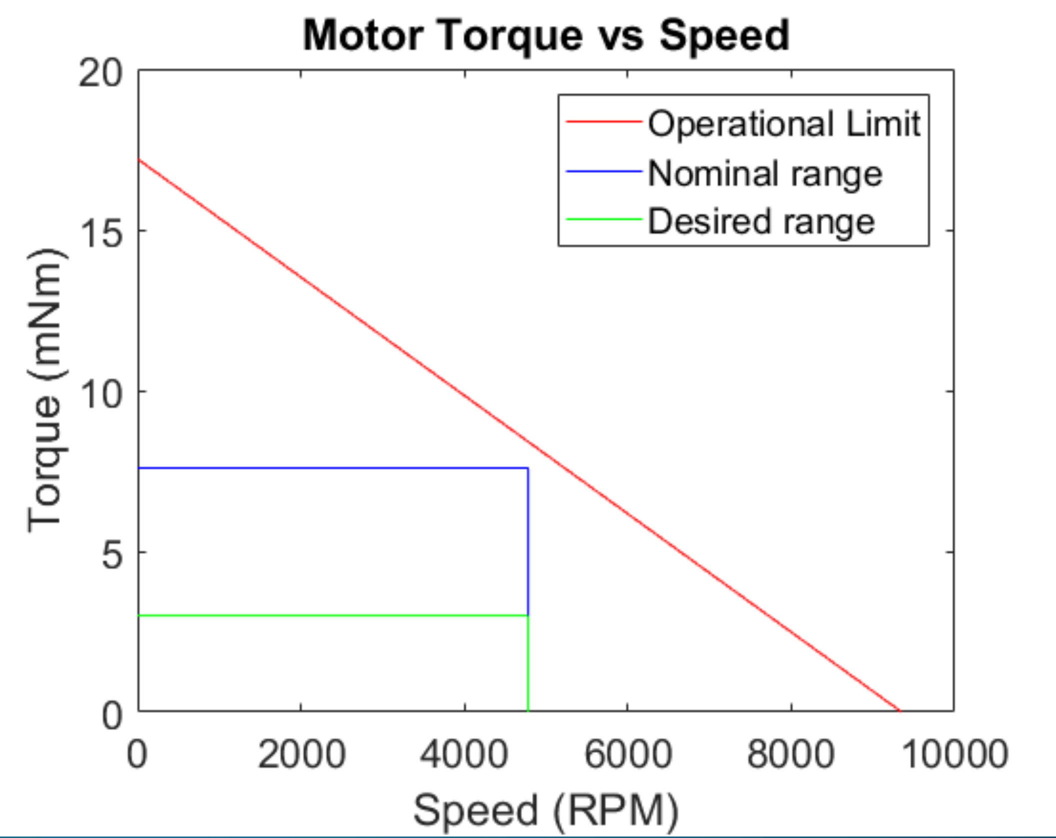


With 640 pixels wide and θ = 21°:

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

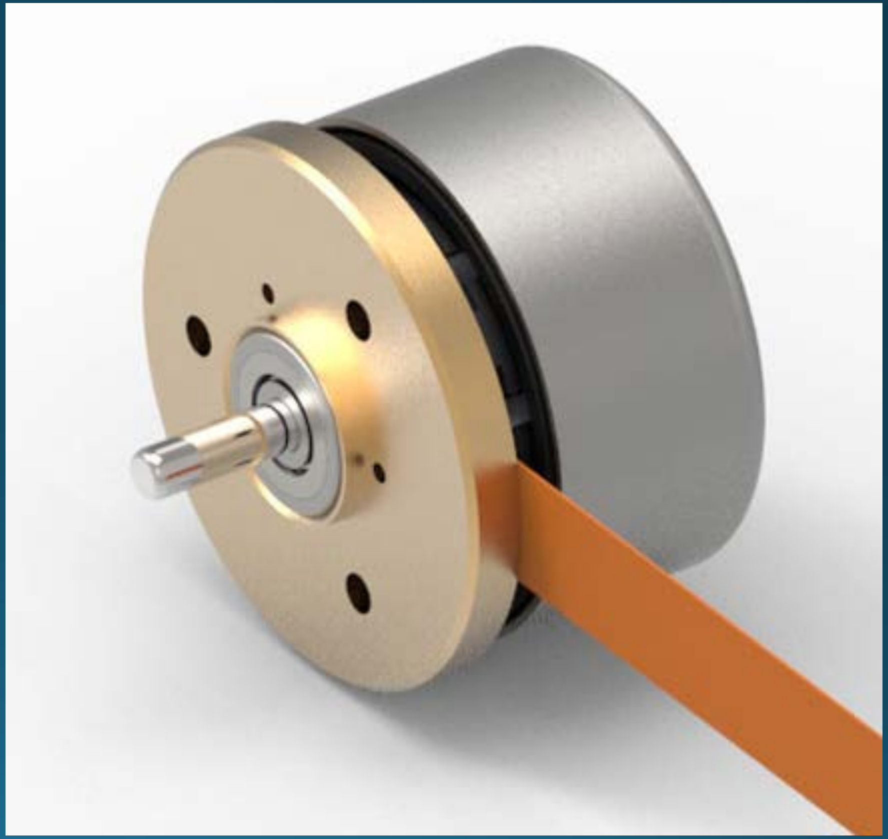
Attitude Control: Motors

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



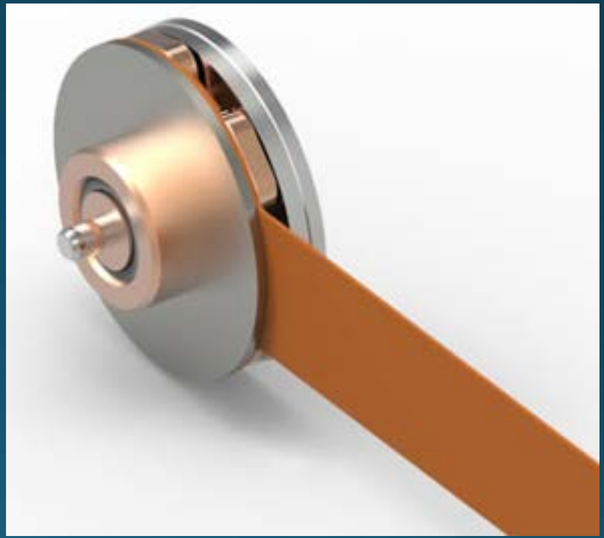
Attitude Control: Motors

- 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



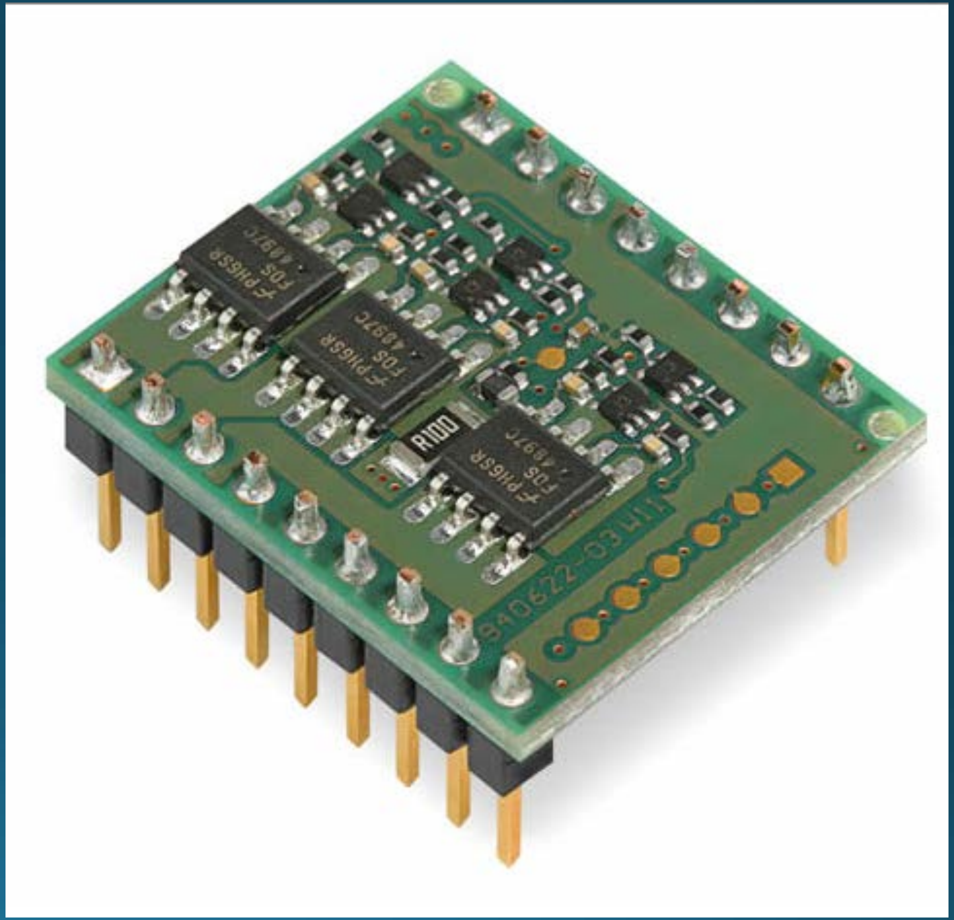
Attitude Control: Motors

- 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



Attitude Control: Sensors

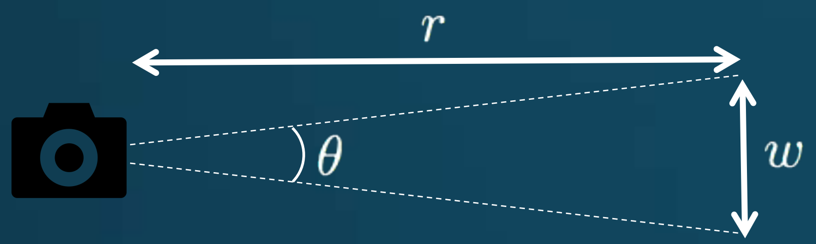
Nomenclature

X_t Target Variable

X_f Fine Sensor Variable

X_c Coarse Sensor Variable

Pointing Windows:



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

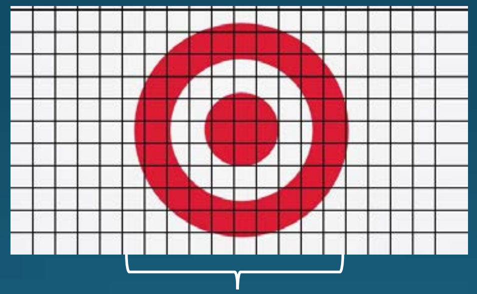
$$L \equiv \frac{meters}{pixel}$$

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

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

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

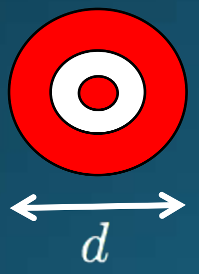
Assume at least 10 pixels across target window → Minimum meter per pixel ratio



10 pixels

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

Target Size:



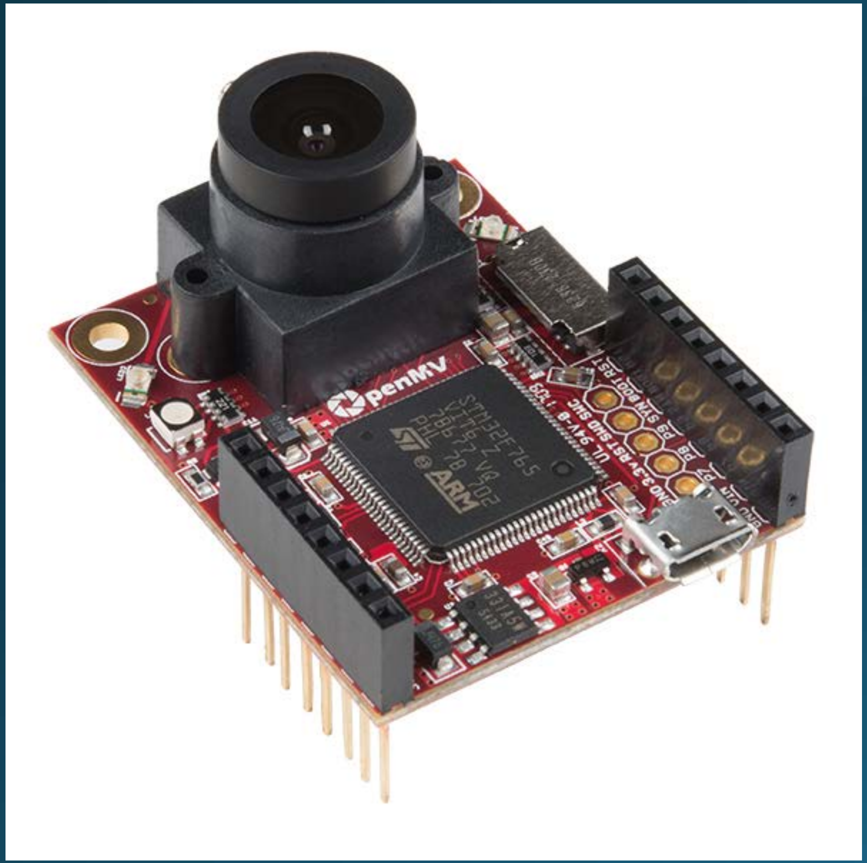
$$d \in [0.0027, 0.0533]\ m$$

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

Attitude Control: Sensors -Pixy Alternative



OpenMV M7 Camera

- 216 MHz Processer
- 54 Mbs SPI Bus
- I2C, Can, and TX/RX Buses
- Built in ADC/DAC
- 640x480 8-bit grayscale at 30 FPS

Microcontroller

Atmel SAM E70

- Atmel Studio
- Price: 40 USD
- Scripted Programming
- Familiar among team

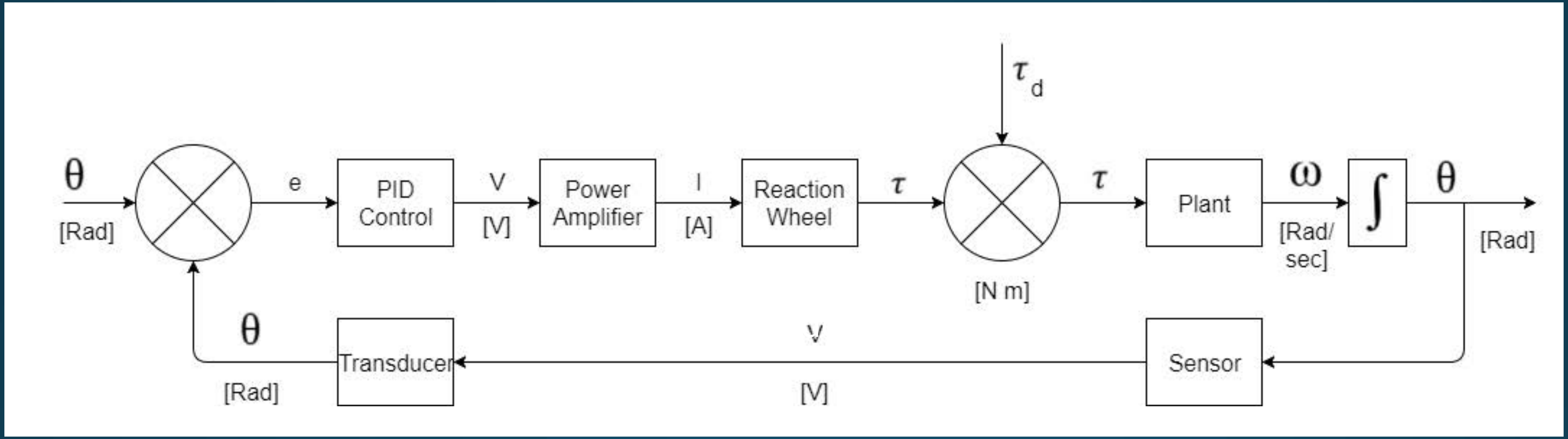
NI myRIO-1900

- NI LabVIEW
- Price: 535 USD
- Graphical programming
- Steeper Learning Curve

Final MCU considerations

MCU	CLK	GPIO	ADC	DAC	RAM	ROM	Peripherals	Features
Atmel SAM E70	300 MHz	144	24 ch. 12-bit 2Msps	2 ch. 12-bit 1Msps/ch	384kB	2MB	SPI UART/USART I2C USB	32 bit FPU Comparator
NI myRIO-1900	667 MHz	24	500 kS/s 12 bit	345 kS/s 12 bit	256 MB DDR3	512 MB	SPI PWM Quadrature I2C UART	FPGA Dual core Wireless capable

ADCS Bandwidth



- -3 dB cutoff frequency is 0.04 Hz
- All components of the ADCS are well within bandwidth of the controller
  - ATMEL SAM E70 – 300 Mhz
  - Maxon motor controller – 100 kHz
  - Pixy – 10 Hz – 2.5 Decades above Bandwidth

Requirements Flow-down

1. The TestTable shall provide for 3DOF dynamics in a reduced-friction environment.
    1.1. The TestTable shall allow for two degrees of freedom in translation and one degree of freedom in rotation.
        1.1.1. The TestTable shall allow for simultaneous, unrestricted translation along two orthogonal axes within a designated portion of the plane of the TestTable surface.
        1.1.2. The TestTable shall allow for unrestricted rotation of the MockSat about its axis normal to the plane of the TestTable surface.
    1.2. The TestTable shall support the weight of the MockSat whilst providing for a reduced-friction surface.
        1.2.1. 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 TestTable material (i.e. polycarbonate).
    1.3. The TestTable shall comply with OSHA Two-Man Lift criteria.
        1.3.1. The TestTable shall occupy a volume no greater than 72 x 72 x 28 inches.
        1.3.2. 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, the coarse orientation sensor, 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 agnostic 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

[1] Chapel, J. (2014). *Guidance, Navigation, and Control Performance for the GOES-R Spacecraft. Porto, Portugal. ESA*

[2] Rozelle, D. *The Hemispherical Resonator Gyro: From Wineglass to the Planets*

[3] Hubble Space Telescope Hot and Cold Pixels. Space Science Telescope Institute. http://www.stsci.edu/hst/nicmos/performance/anomalies/hotcoldpix.html