Test Readiness Review

Lockheed Martin LLAMAS Team

sateLLite ADCS fault MAnagement System

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Mission Objective

- 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.

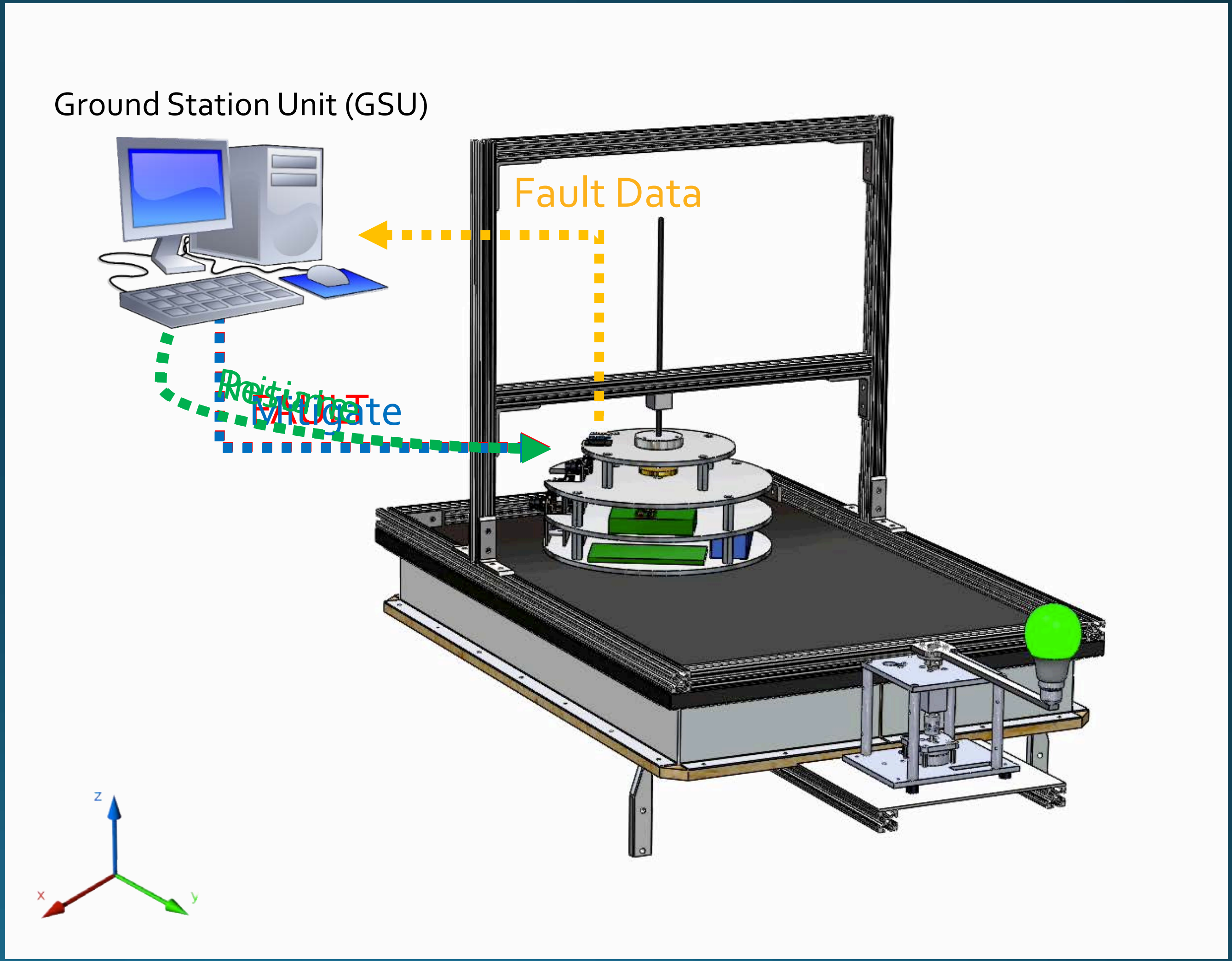
Project Overview

Levels of Success

	Level 1	Level 2	Level 3
TestTable	Construct a TestTable to allow for 2D translation dynamics with passive control, 1D rotation dynamics, support weight of MockSat, stationary attitude reference		Moving attitude reference
MockSat Hardware	Power source, orientation sensor, coarse orientation sensor, fine orientation sensor, redundant reaction wheels, ADCS/fault injection processor, data storage, 15 minute constant operating time	30 minute constant operating time	60 minute constant operating time
Fault Injection	Inject fatal operating fault into primary reaction wheel after pre-determined time from testing start	Inject fatal operating fault into coarse sensor	
Fault Management	Upon fault injection, the MockSat will recognize the presence of the fault and enter a safe mode		Upon user command, MockSat responds in a way that maintains operational integrity
MockSat Control	Active planar rotational control with passive translational control		
Comm/Data Handling	Flight software and fault uploaded prior to testing, telemetry data stored on-board MockSat, Ground Station data analysis post-test	Wired, real-time telemetry and fault injection	Wireless, real-time telemetry and fault injection

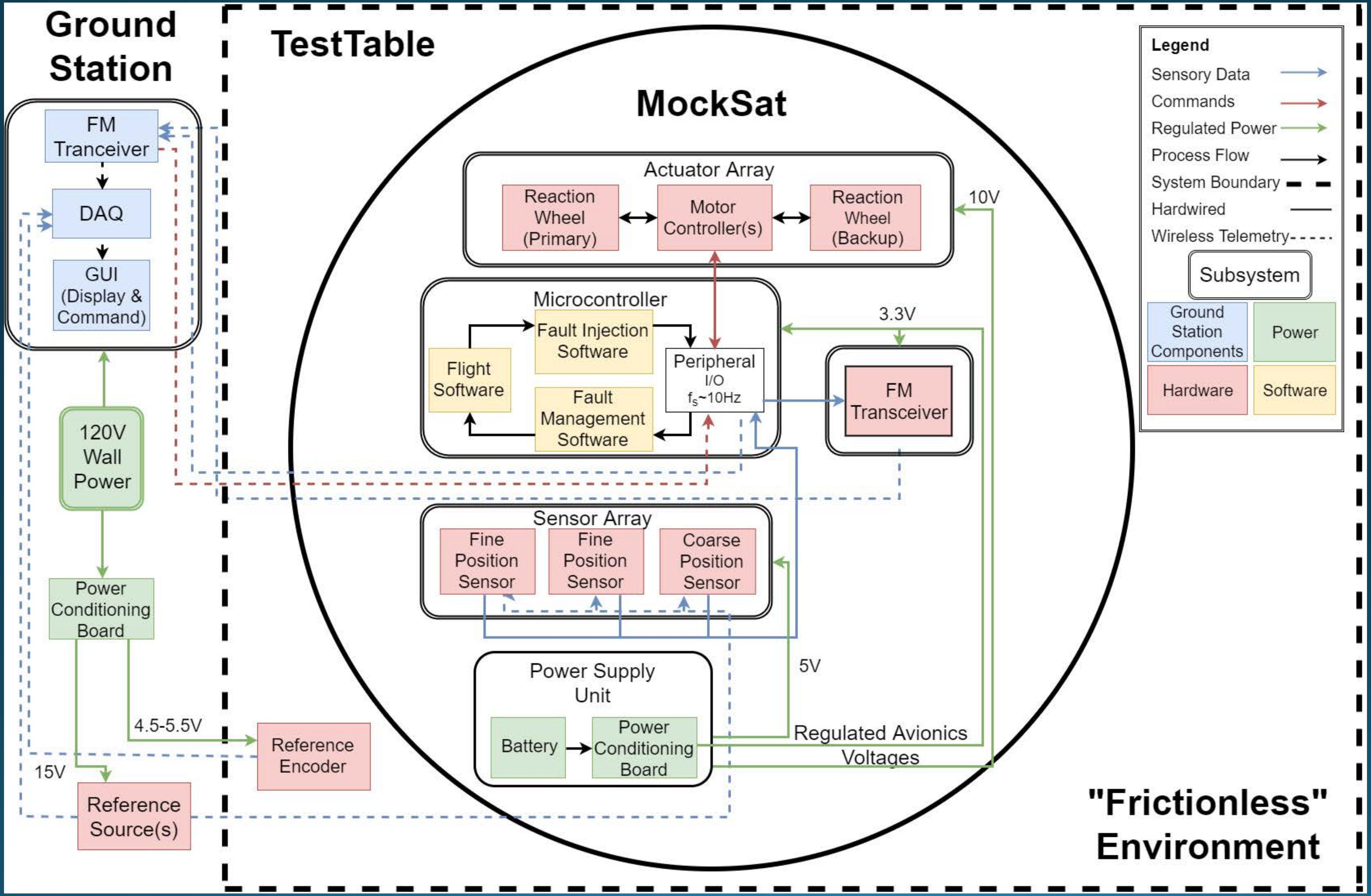
Concept of Operations (CONOPs)

- 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 (accelerated playback)

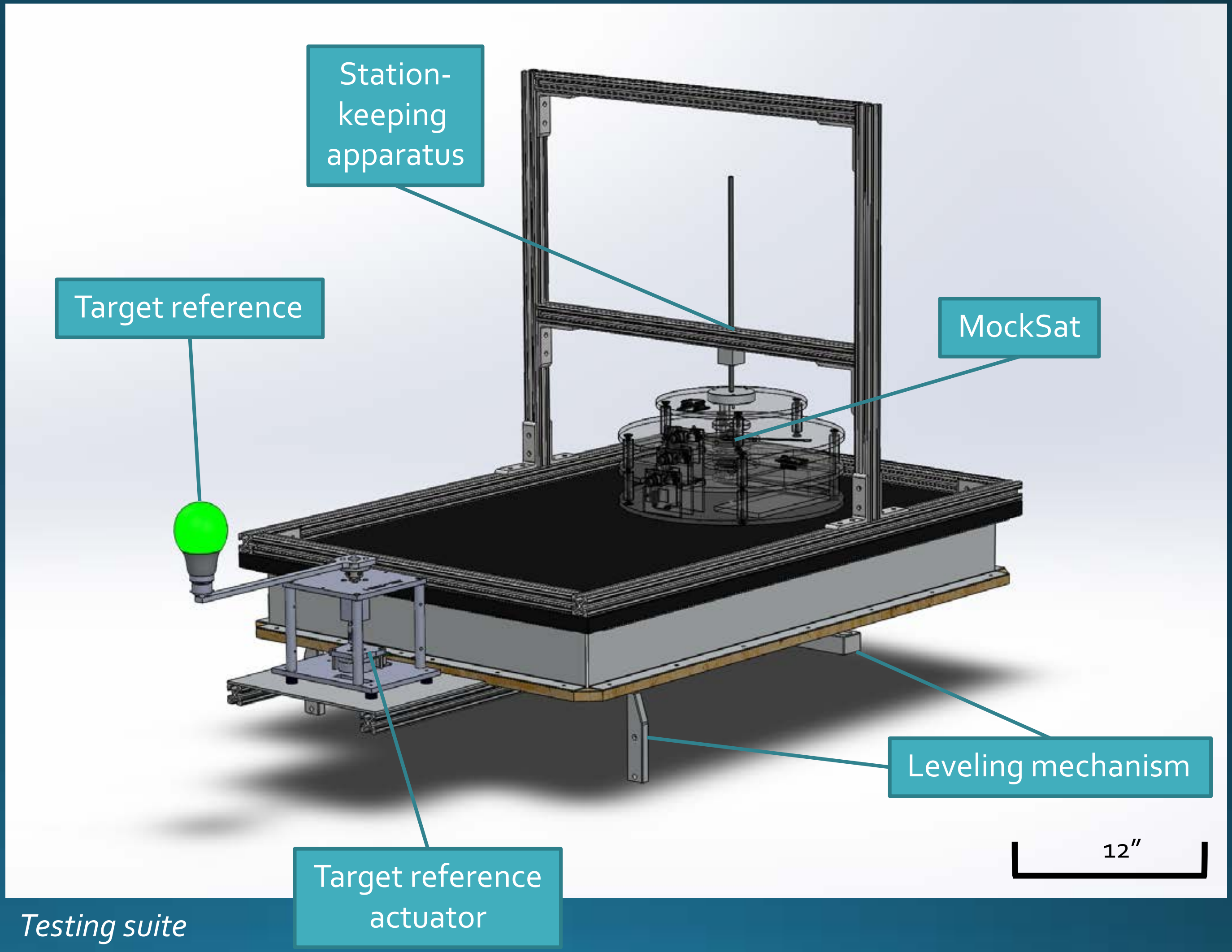
Functional Block Diagram (FBD)



Baseline Design – TestTable

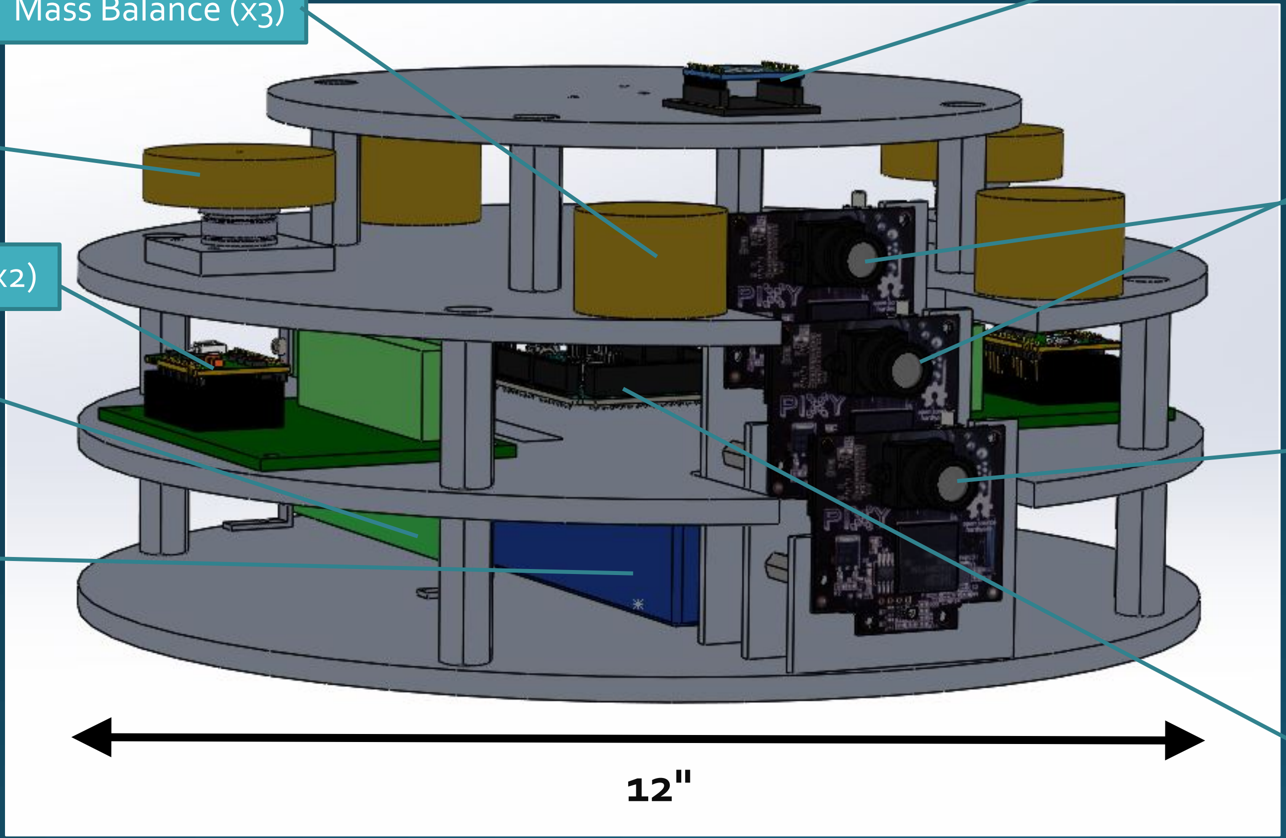
The majority of the TestTable is heritage equipment from the *TracSAT* senior project, with the following modifications:

- 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

Baseline Design – MockSat



MockSat Concept

Total Weight	13.6 lbm
MOI about Axis of Rotation	237.2 $lb*in^2$
Height	5.9 in
Width	12 in

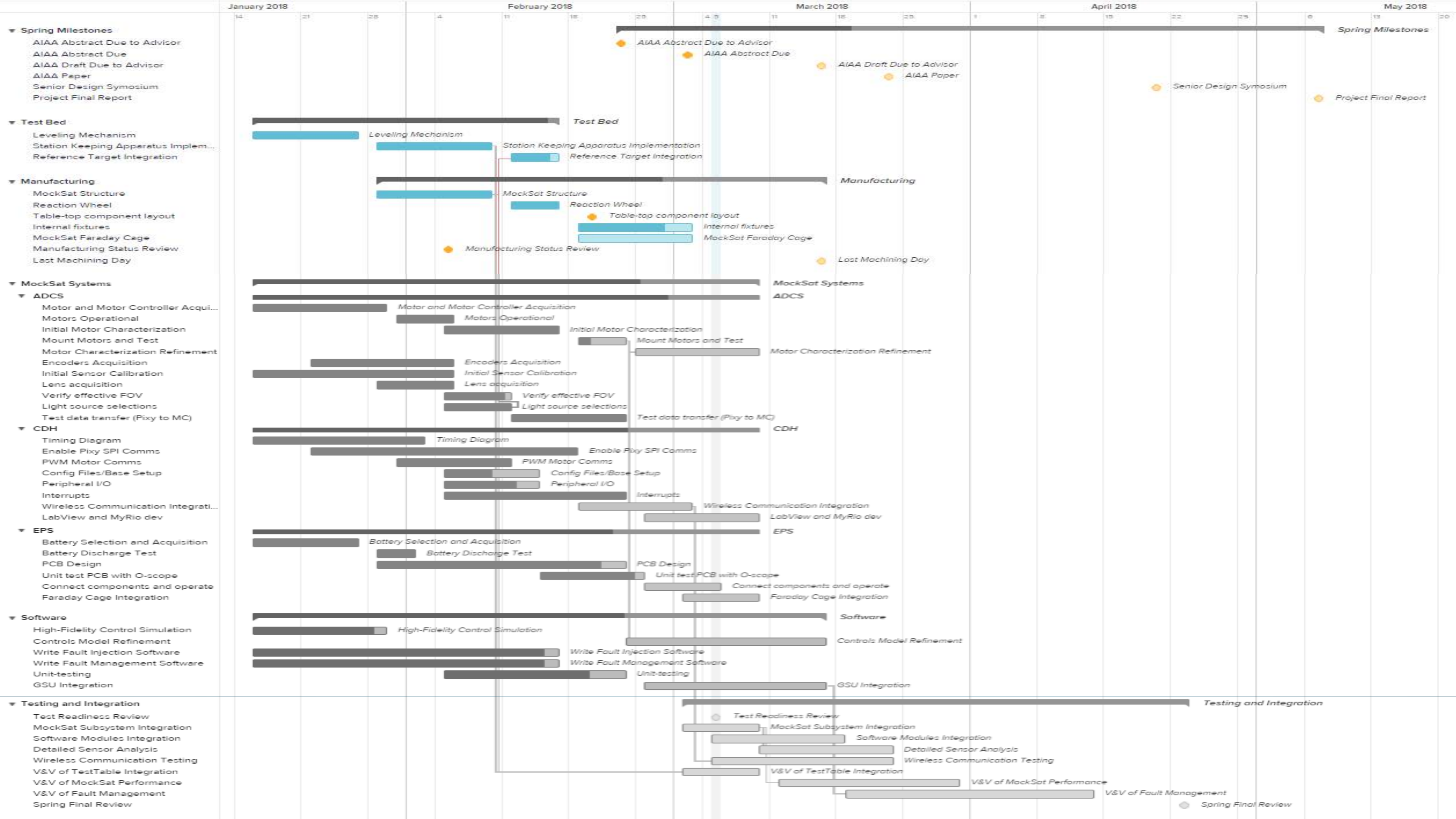
Critical Project Elements - Motors

- Proper motor selection will enable team to meet control system bandwidth requirements.
- Careful and accurate characterization of motor performance and internal friction of the motors is needed for both the control system and the ability to introduce reaction wheel faults.

Critical Project Elements - Fault Injection and Management

- Ultimate goal of the project revolves around fault management.
- The ability to introduce faults requires testing and characterization of the entire MockSat system.
- Difficult to test and evaluate until the various subsystems have been characterized and fully integrated into the MockSat system.

Schedule



January 2018
February 2018
March 2018
April 2018
May 2018
Spring Milestones
AIAA Abstract Due to Advisor
AIAA Abstract Due
AIAA Draft Due to Advisor
AIAA Paper
Senior Design Symosium
Project Final Report
Test Bed
Leveling Mechanism
Station Keeping Apparatus Implementation
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Manufacturing
MockSat Structure
Reaction Wheel
Table-top component layout
Internal fixtures
MockSat Faraday Cage
Manufacturing Status Review
Last Machining Day
MockSat Systems
ADCS
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Mount Motors and Test
Motor Characterization Refinement
Encoders Acquisition
Initial Sensor Calibration
Lens acquisition
Verify effective FOV
Light source selections
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PWM Motor Comms
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Software Modules Integration
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V&V of TestTable Integration
V&V of MockSat Performance
V&V of Fault Management
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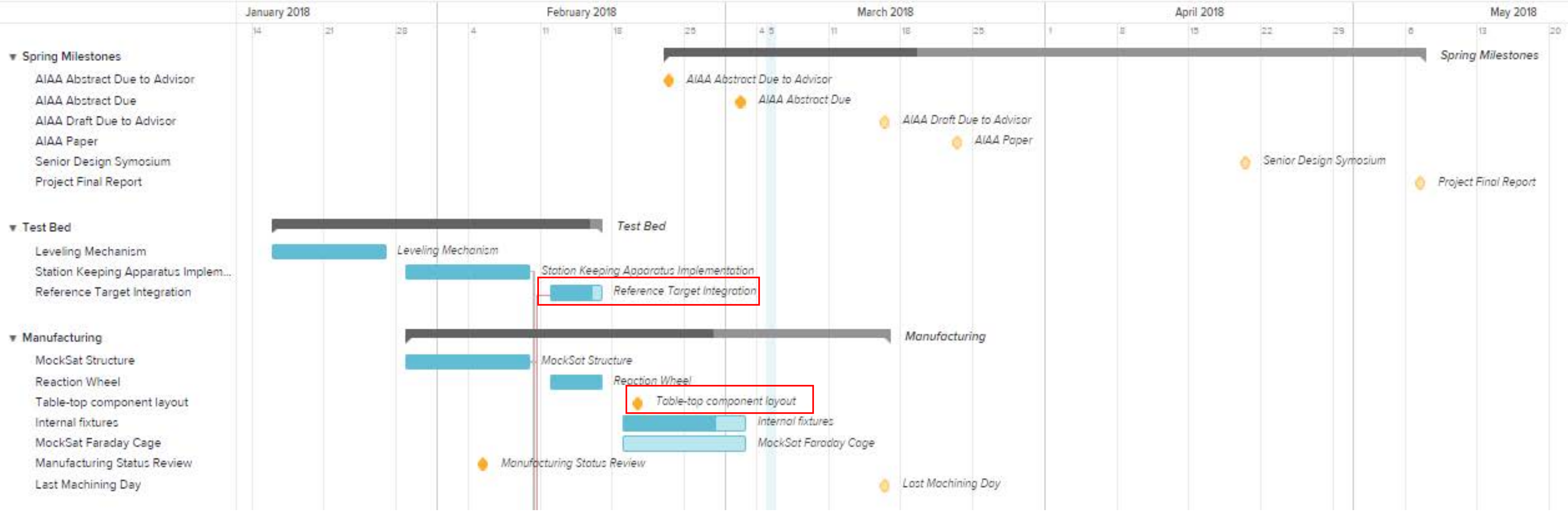

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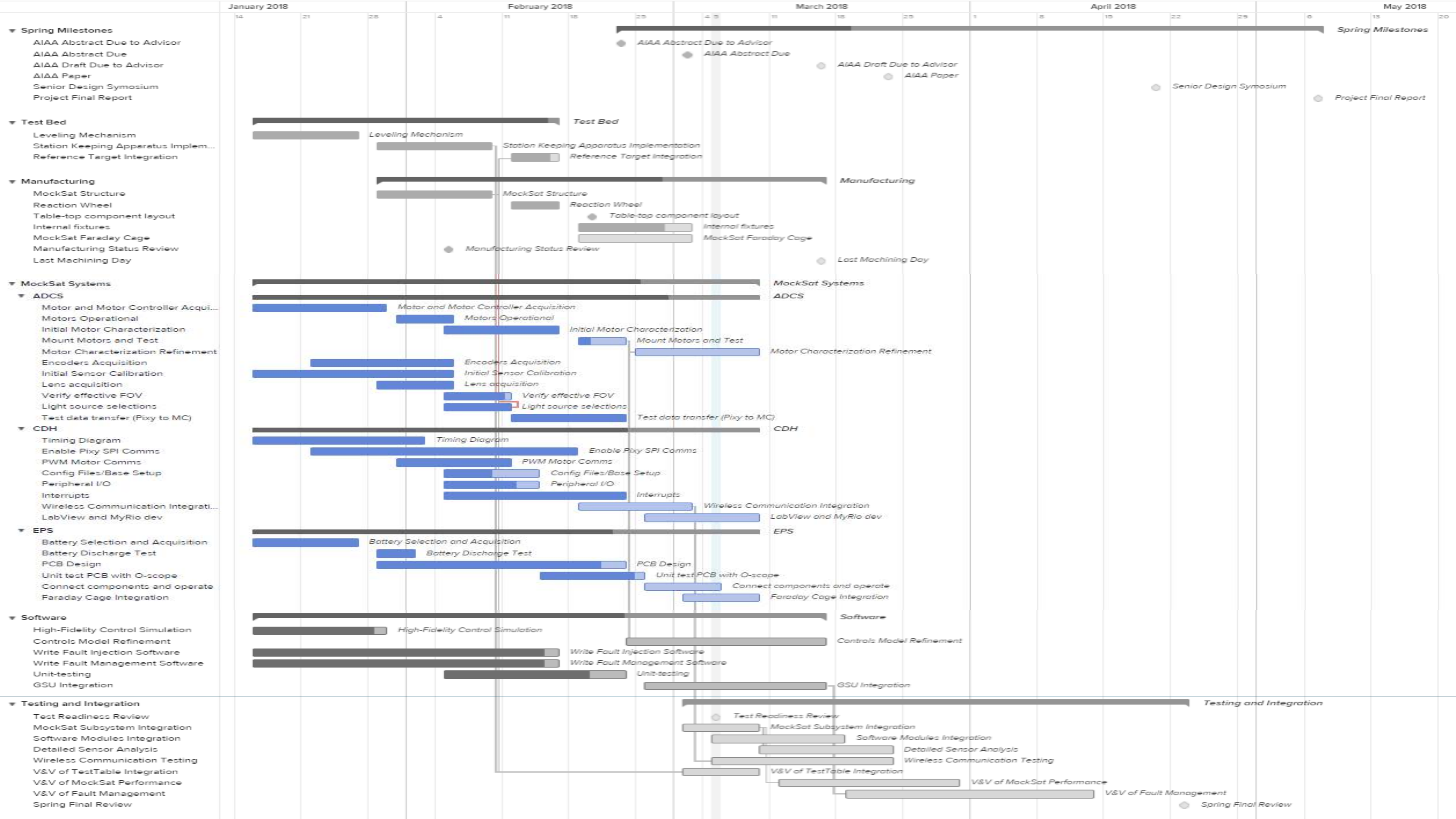
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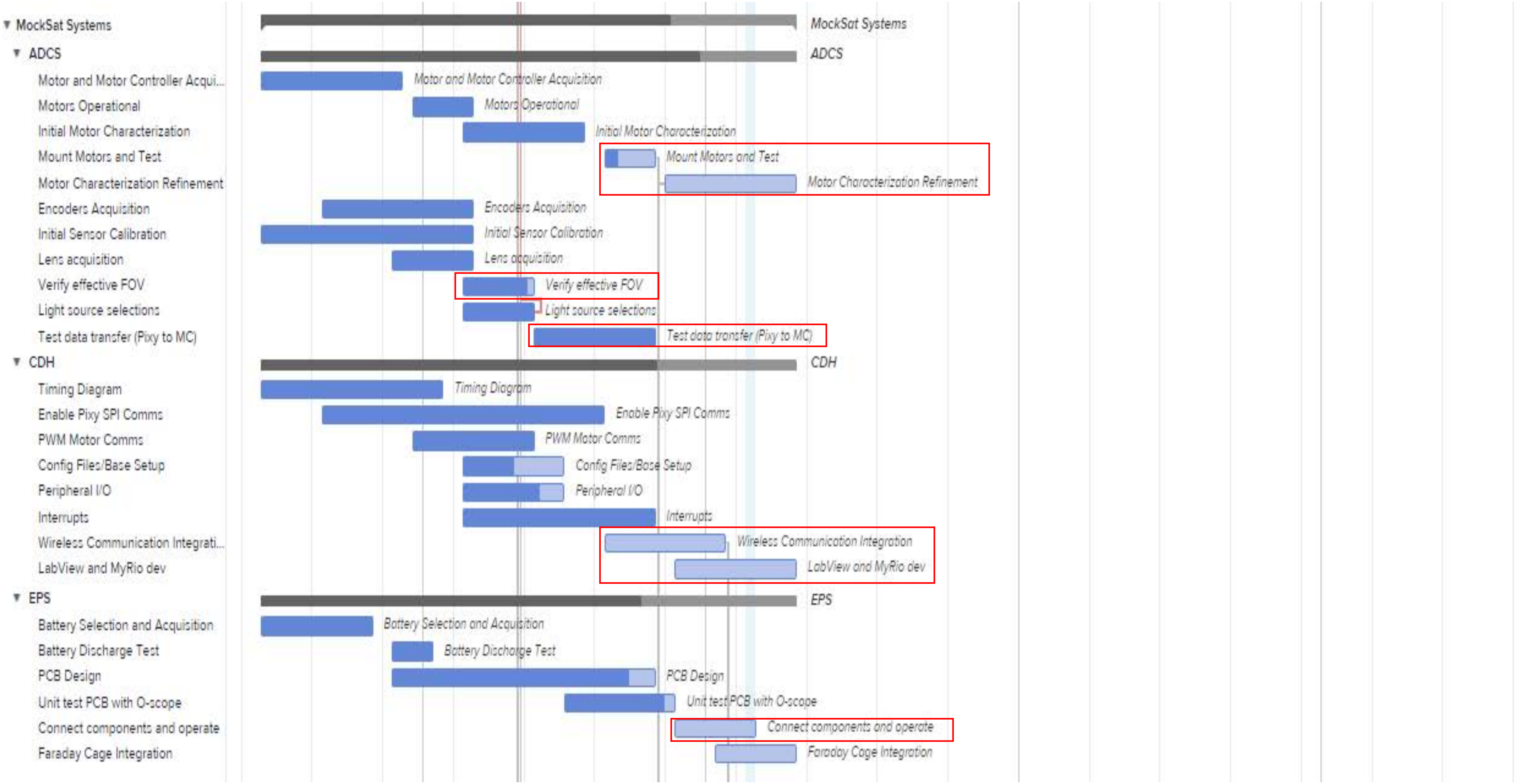
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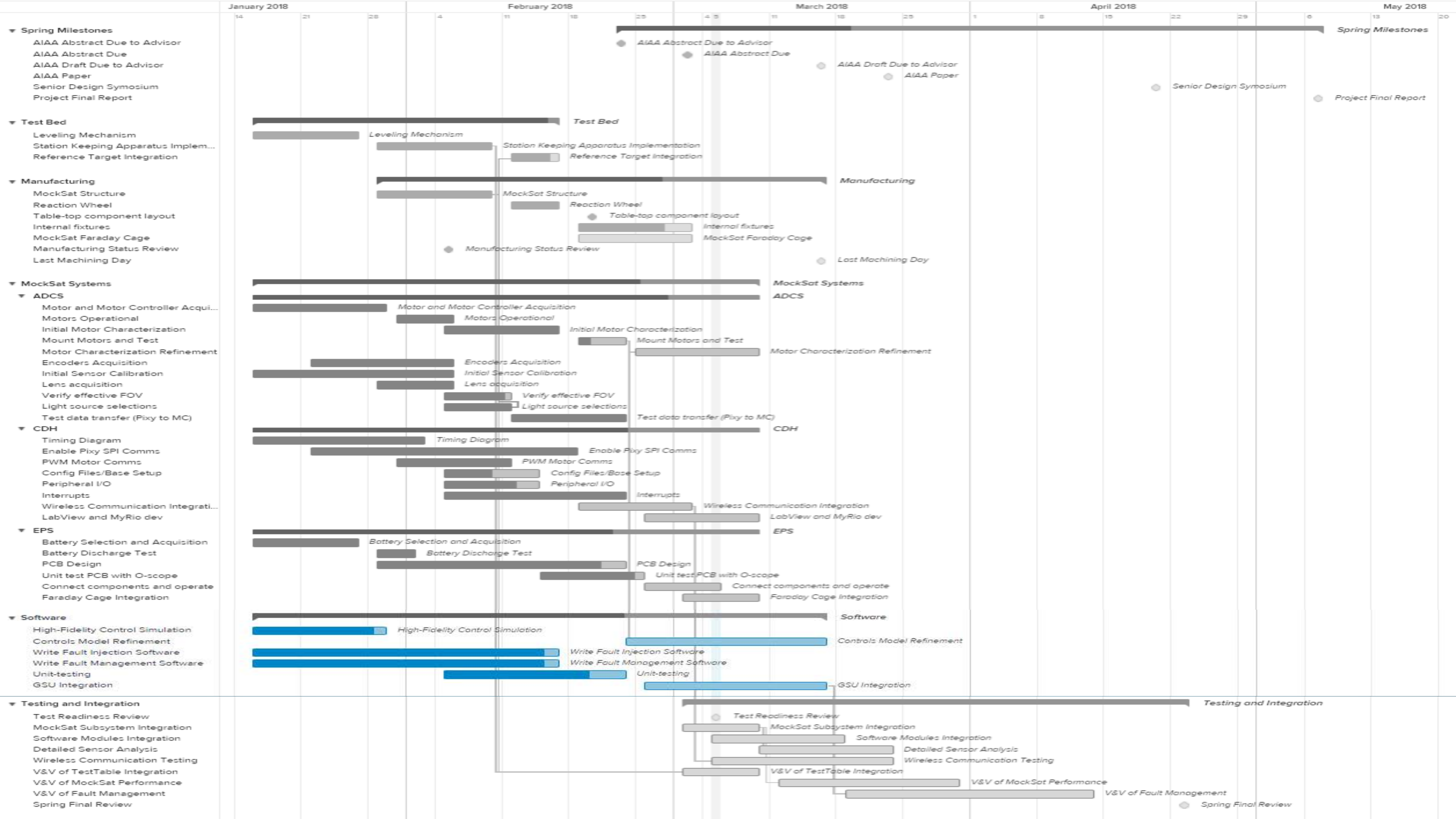
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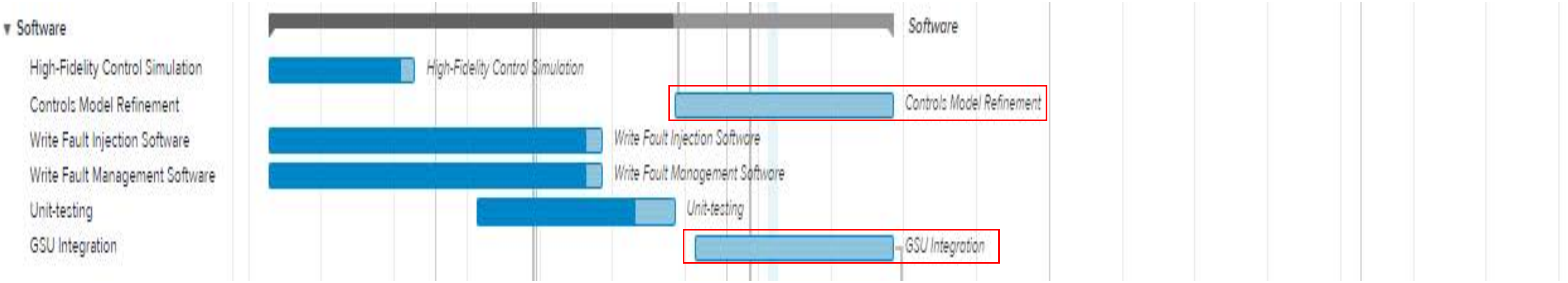
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January 2018
February 2018
March 2018
April 2018
May 2018
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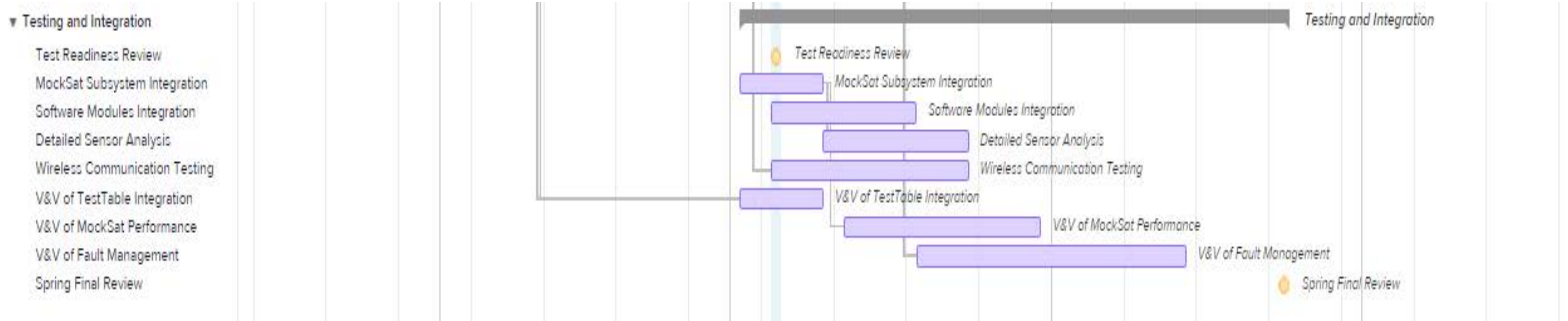
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Test Readiness

Attitude Determination and Control System

- **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 to within ±2.5°.

ADCS – Pixy Unit Testing

Purpose: Demonstrate ability of Pixy to determine relative pointing of MockSat

Method: Measurements of what the Pixy sees in a known distance environment to compute the effective FOV. Determine preliminary parameters for Pixy detection tuning

Risk Reduction: Ensures selected lens meets required pointing accuracy with smaller CMOS then designed for. Reduces development time for final testing environment.

Equipment: Pixy camera, target source (lightbulb), PixyMon software, measurement device (yardstick)

Note: Since there is such a large margin in both fine and coarse sensor performance vs. the requirements, the level of detail in the characterization does not need to be precise (i.e. distance measurements with an accuracy of 1/16” is sufficient)

Results: Average loss from advertised horizontal FOV to actual FOV ~40%. Vertical FOV is ~60% of horizontal FOV. This allows for accurate modeling and selection of target motion to remain within view of the Pixys.

25%	50%	75%	95%

ADCS – Pixy Integration Testing

Purpose: Demonstrate ability of Pixy to communicate selected data with MCU

Method: Connect Pixy to Arduino. Test if developed software communicates required values. Then feed these values into a simplified control law for a servo to prototype full system.

Risk Reduction: Develops a baseline model for full system integration, as well as checking Pixy to Arduino communications.

Equipment: Pixy camera, target source (lightbulb), Arduino, Servo

Results: Pixy was able to successfully control servo through simplified controls. Pixy will be able to interact with final development solution.

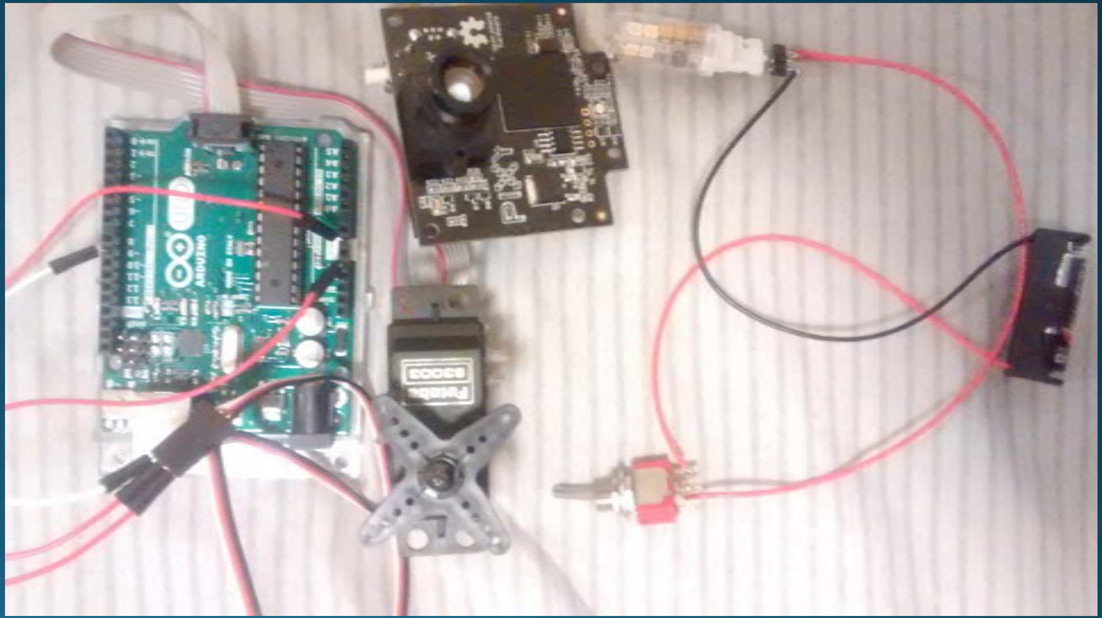


Figure: ADCS Prototype

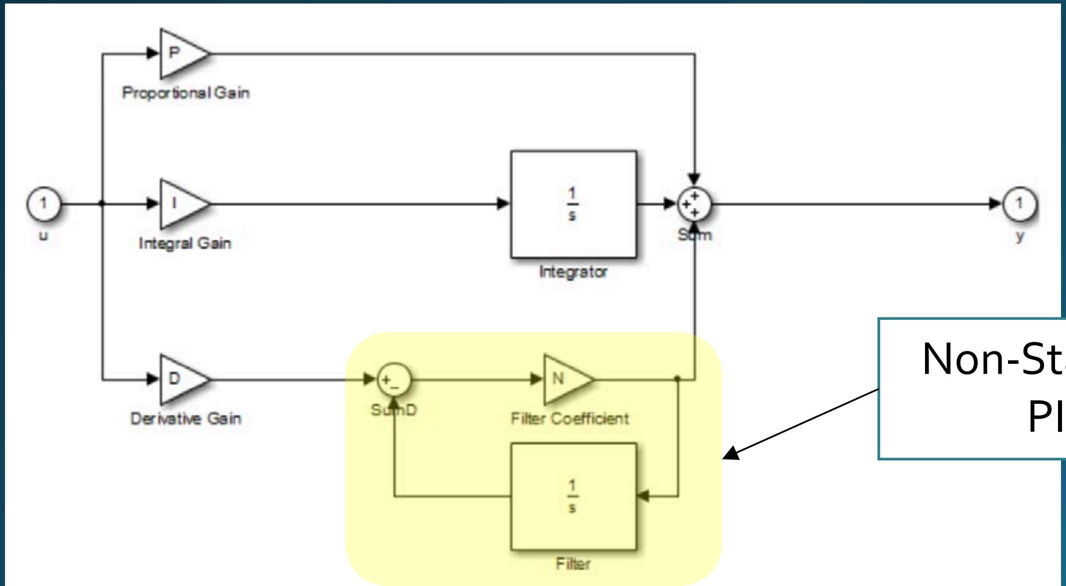
25%	50%	75%	100%

ADCS – Control Unit Testing

Purpose: Confirm PID control law on the Arduino agrees with the SIMULINK model.

Method: Record both responses to a step command and compare results.

Risk Reduction: Augment PID in Arduino

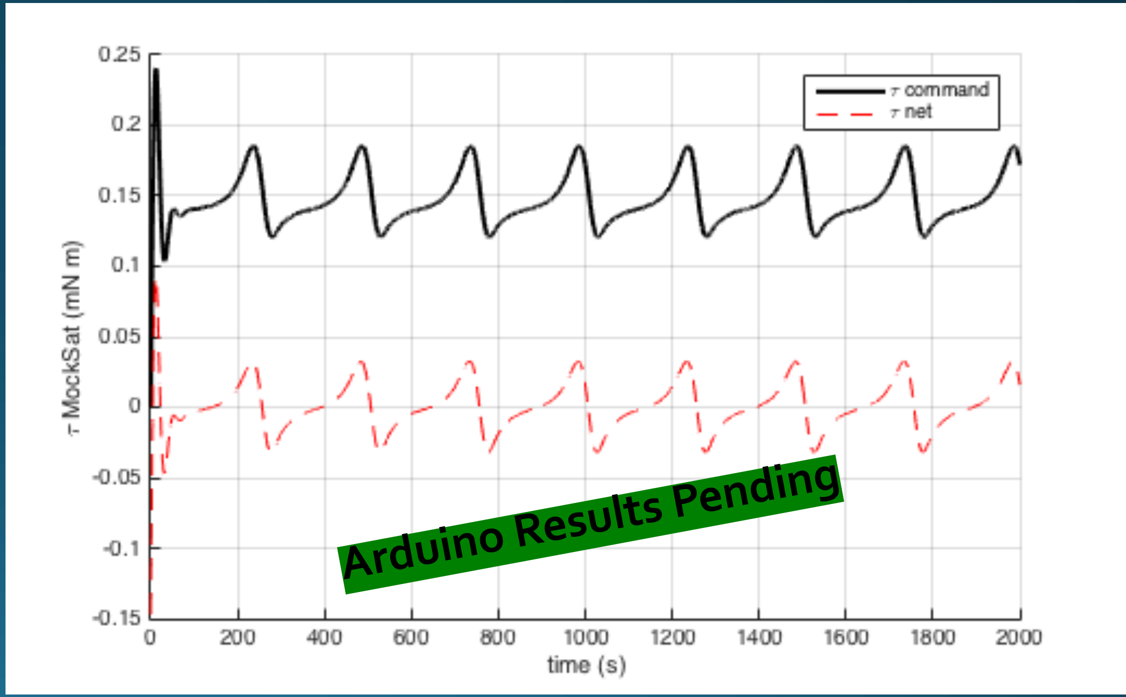


Non-Standard PID

Equipment: MATLAB/SIMULINK, Arduino

Note: Waiting on PID patch in Arduino.

Results:



25%	50%	75%	100%

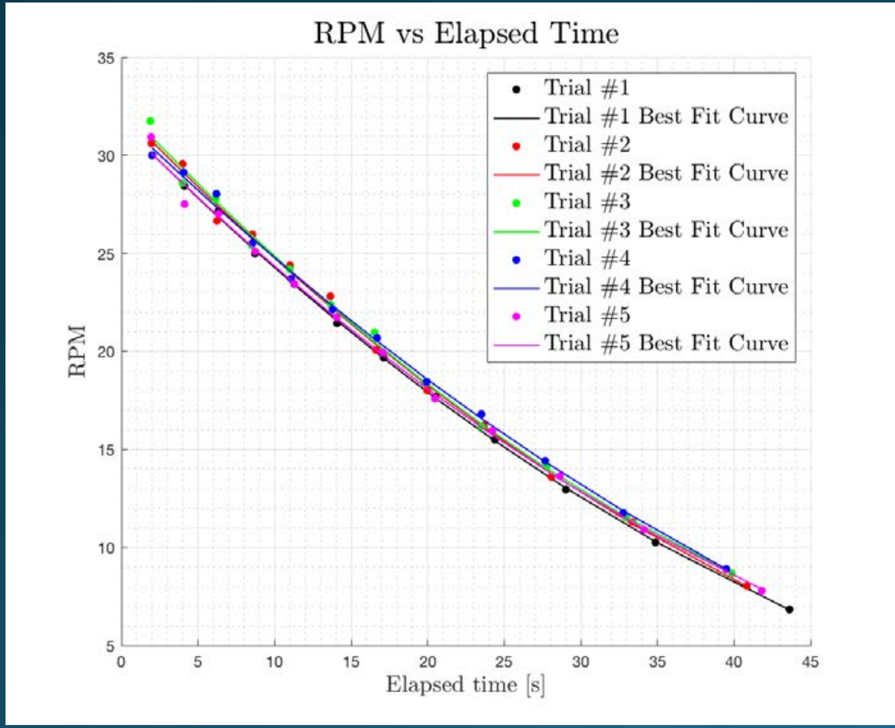
ADCS – Control Plant Validation (TestTable Losses)

Quantification of losses

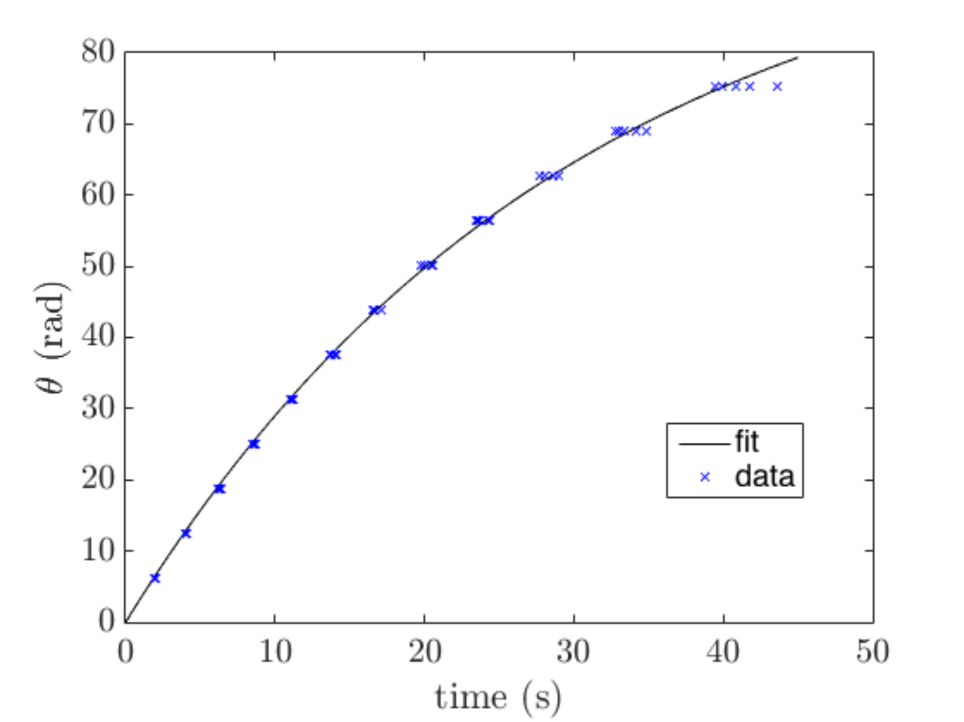
- Key assumption: friction torque varies linearly with angular velocity
- Air friction and bearing block friction measured simultaneously (no need to separate).

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

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



Tested losses for TestTable



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

ADCS – Motor Internal Friction Characterization

Purpose: Characterize Stiction, Coulomb, and Viscous Friction

Method:

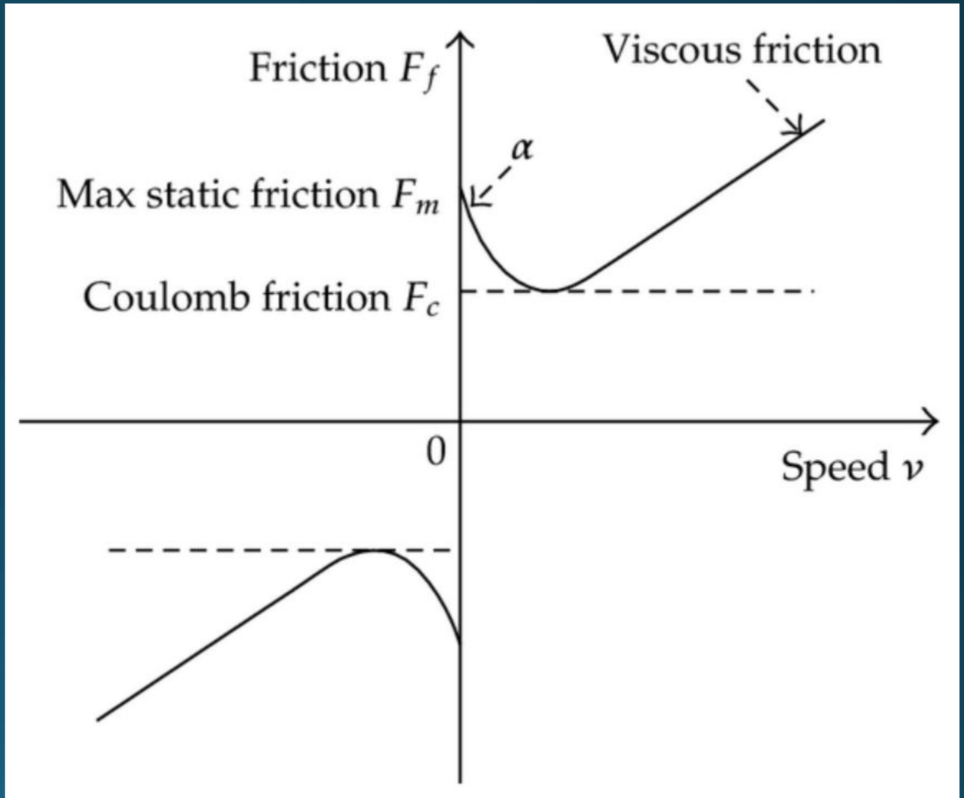
Stiction- Starting with the motor at rest, increase the commanded torque until the motor begins to commutate.

Coulomb- Start the motor such that the rotor has an initial angular velocity, then gradually decrease the commanded torque until the rotor ceases to commutate.

Viscous- Command two torques which result in overall zero net torque in the system at different rotor speeds. Current can be converted to torque using constant from data sheet. Motor should accelerate until Coulomb and Viscous friction equal applied torque.

Relevance: **Friction characterization is required for control law and fault management and injection systems.**

Equipment: DC power supply, Labview, Escon Studio,



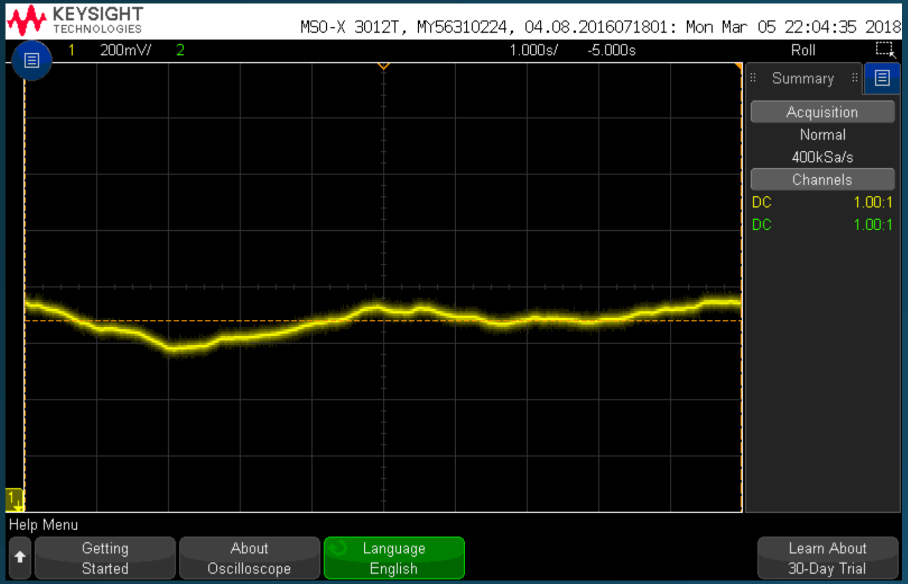
Frictional components as a function of rotor speed

$$\tau_{net} = \tau_{applied} - \tau_C - \tau_V = 0$$

ADCS – Challenges to Torque Characterization

Purpose: Characterize torque resolution and consistency applied to MockSat from motors

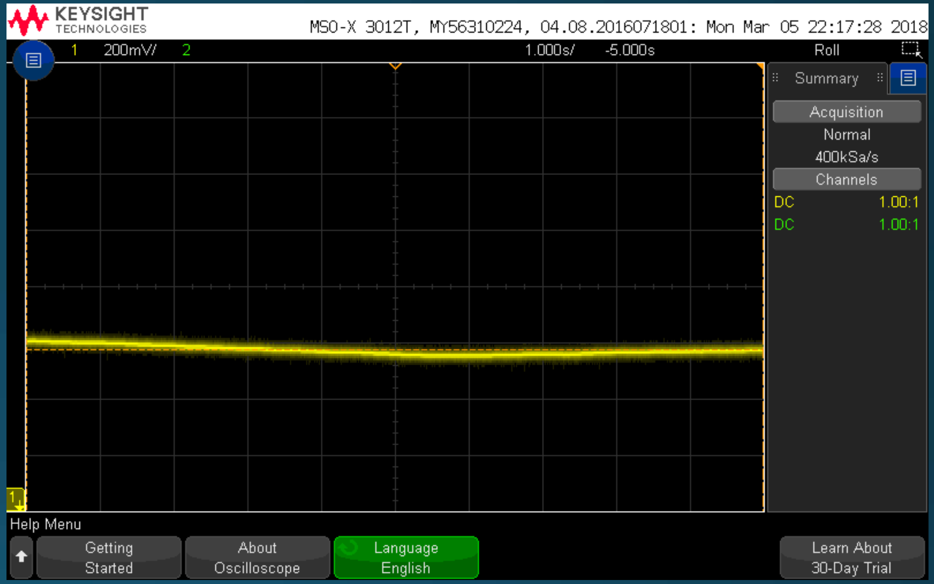
Equipment: DC power supply, Labview, Escon Studio, Oscilloscope



Rotor speed at constant applied torque without reaction wheel

Δt = 10 seconds

500 mV = 1000 rpm



Rotor speed at constant applied torque with reaction wheel

Relevance: Angular velocity of rotor is difficult to maintain without reaction wheel. Fitting a reaction wheel increases torque consistency and also results in a wider range of effective operation since lower rotor speeds are induced for a given command. Results in longer test times without risking saturation.

Verification and Validation – Bandwidth Response

Purpose: Determine bandwidth of the MockSat via Bode plot characterization

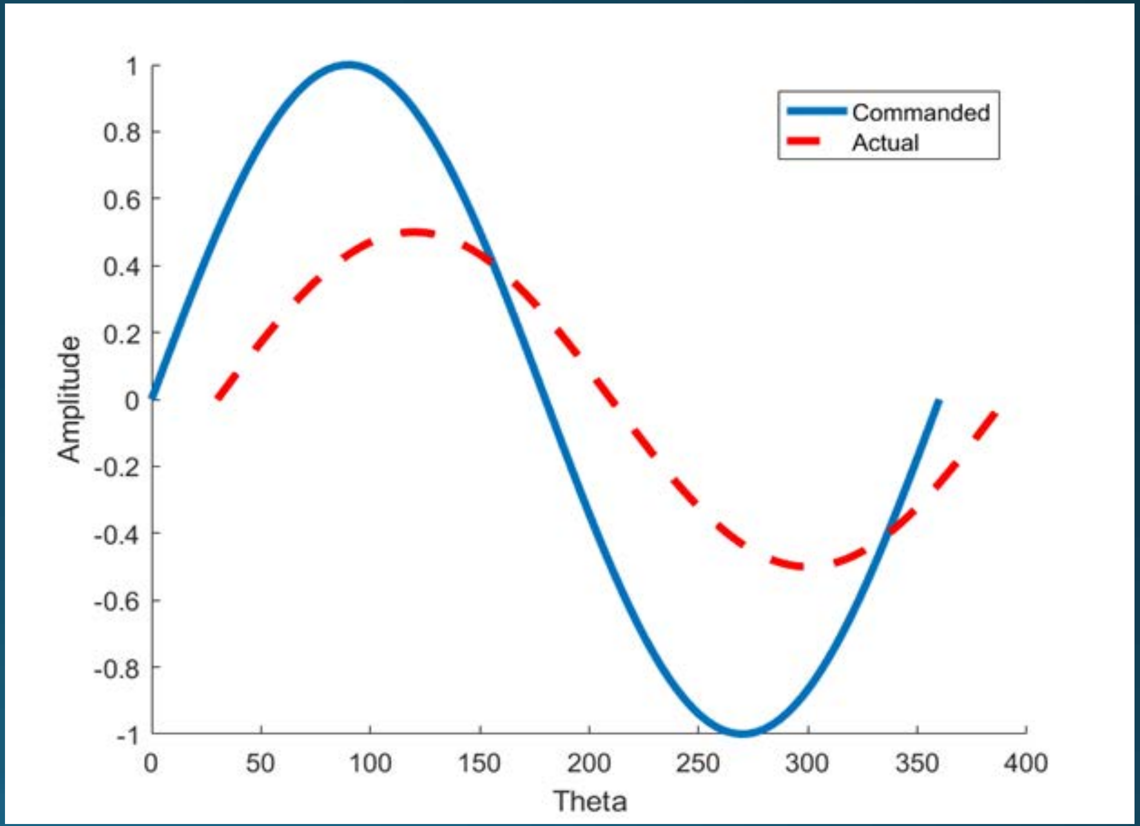
Requirements Validated:

- Replicates the 0.04 Hz bandwidth within ± 10%

Location: Lockheed Martin Projects Room

Method: Command the MockSat with sinusoidal inputs spanning a decade before and after the corner frequency of 0.04 Hz. (0.004 - 0.4 Hz). Measure the magnitude response for each frequency of input commands to determine the bandwidth response.

Breakdown:



Plant response for an input command at the corner frequency of 0.04 Hz.

Verification and Validation – Pointing Accuracy

Purpose: Determine pointing accuracy of the MockSat

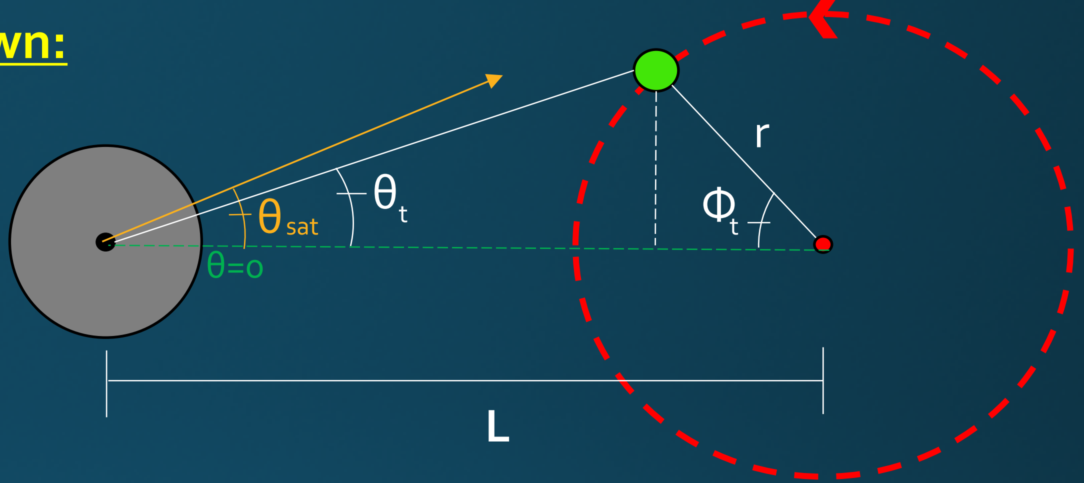
Requirements Validated:

- 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**

Fault Injection (FI) and Fault Management (FM)

- **Functional Requirement 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).

- **Functional Requirement 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.

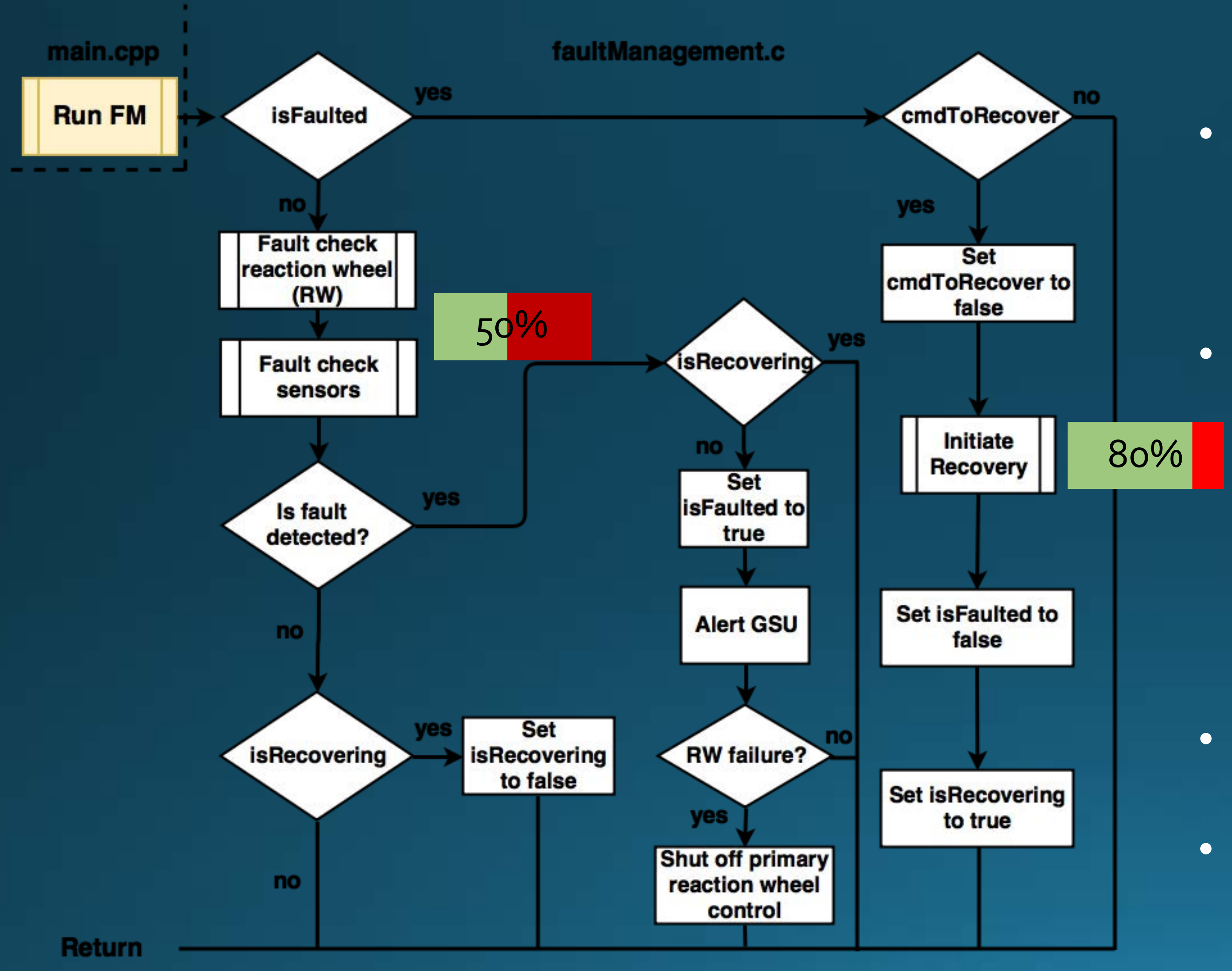
*a fatal operating fault is defined as preventing $\pm 2.5^{o}$ pointing accuracy

FI & FM Testing: Unit Testing

FI FM

Function	Inputs	Outputs	Verified?	Comments
injectFault.c	IsPrimaryRWactive, cmdToFaultRW, ω, p1, p2	$\hat{\tau}_c$	100%	• Injection ready for integration testing
calcInducedFric.c	ω, p1, p2	Induced friction	100%	
recovery.c	faultType	Switch command to secondary device	80%	• Needs to be able to switch command b/w reaction wheels
faultCheck.c	faultType, faultTimeActive	faultType	30%	• Had to redo logic and timer
checkThreshold.c	$\Delta\theta$, ω, $\hat{\tau}_c$	faultType	80%	• Tested with ASEN 3200 data

FI & FM Testing: Unit Testing



- A series of inputs (reaction wheel speed, current location, commands from ground station) are tested to verify each scenario works
- At a minimum, 6 tests are ran:
  1. Nominal
  2. Faulted
  3. Waiting for Ground Station Units (GSU)
  4. Initiate Recovery Sequence
  5. Recovering
  6. Recovered
- Monitoring the output from isFaulted, faultType, isRecovering, faultTimerActive
- Results verify a logical sequence of events

FI & FM Testing: Unit Testing

State	isFaulted	faultType	cmdToFaultRW	faultTimer Active	Is Primary RWActive	cmdTo Recover	is Recovering	Comments
Nominal	0	0	0	0 or 1	1	0	0	• faultTimer can be active and not faulted
Faulted	0	1	1	0	0	0	0	• faultType can be 2
Waiting	1	1	1	0	0	0	0	• Want to see fault visually
Initiate Recovery	1	1	1	0	0	1	1	• Likely still faulting
Recovering	0	1	1	0	0	0	1	• Wait until fault is dealt with
Recovered	0	0	1	0 or 1	0	0	0	• Notice that the command to fault is active

FI & FM Testing: FI Integration Testing

Purpose: To test the ability to inject a fault into the system

Requirements Validated:

- **FR 4**: System shall have the ability to introduce a single fatal operating fault

Method:

- Reaction Wheel Fault: The motor is hooked up to our MCU and the friction is increased by some amount. We expect to see the motor provided less torque roughly around the calculated torque with additional friction (calculate in calcInducedFric.c).
- Pixy Fault: With Pixys hooked up to the MCU, information about a relative target should be skewed by exactly the desired amount set up in the interrupt.

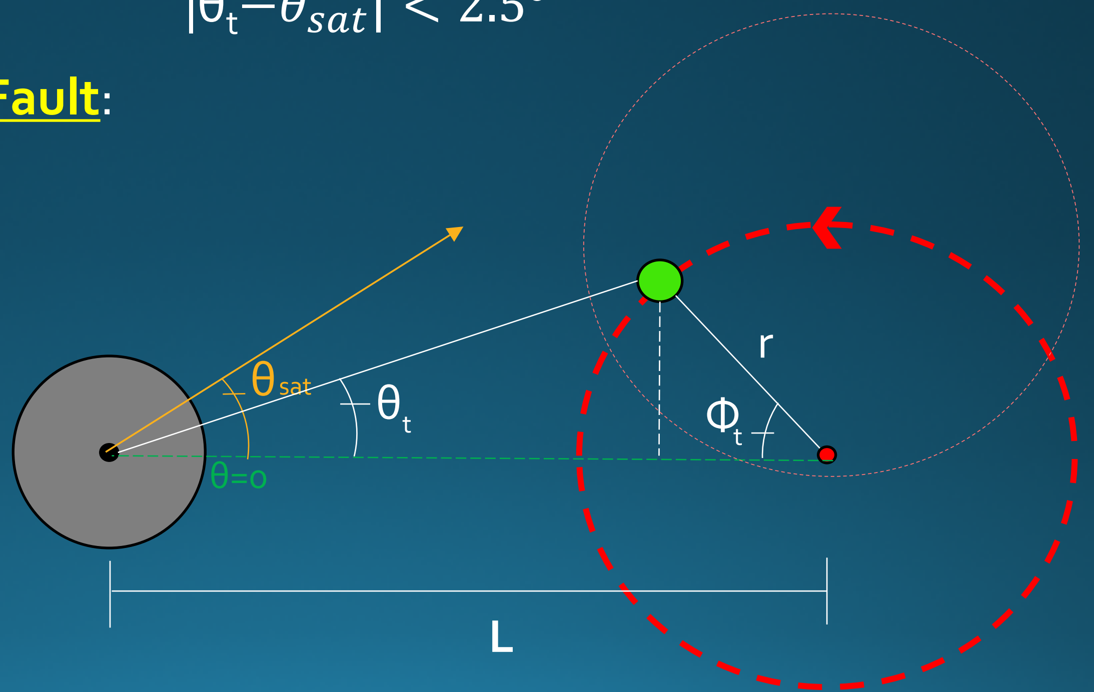
Equipment: Motors, Pixy, Arduino Due

Reaction Wheel Fault:

- Sluggish behavior from MockSat, not able to catch up to target position

$$|\theta_t - \theta_{sat}| < 2.5°$$

Pixy Fault:



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

FI & FM Testing: FM Integration Testing

Purpose: Manage fault by redundant components

Requirements Validated:

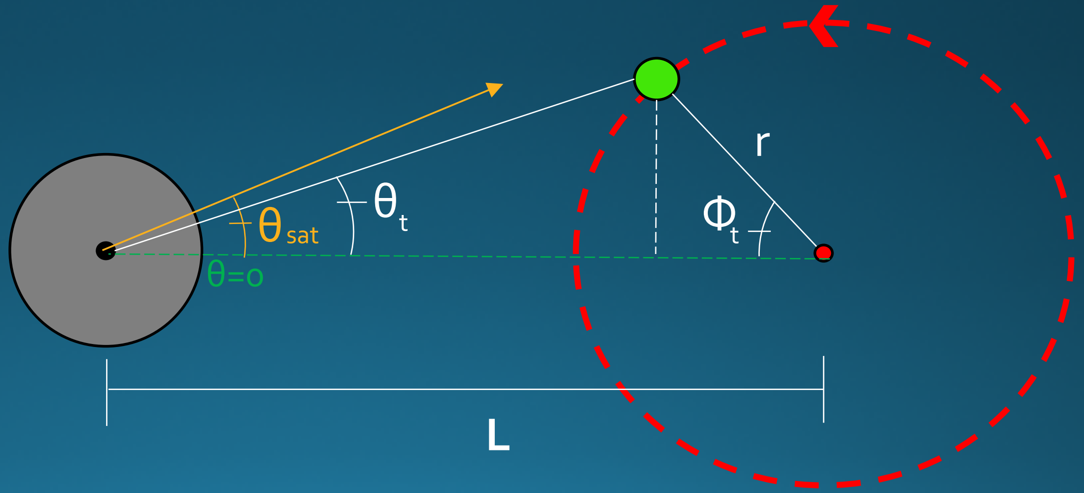
- **FR 5**: MockSat control flight software shall recover from a fatal operating fault

Method: Now with FI functioning, it is possible to test the fault mitigation software by going through previously stated scenarios and monitor bits/hardware.
Eventually tested with Pixys, motors, reference target, and verified with encoder data

Equipment: Motors, Pixy, Arduino Due

Note: Tolerance in timer and threshold values (will have to be tinkered with). First tested by detecting faults in Pixy and motors separately (with no recovery, but while monitoring recovery.c output). Then, tested with redundant hardware (with recovery). Lastly tested when TestBed is completely integrated.

WILL HAVE TO ITERATIVELY TEST TOLERANCES!



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

EPS – Power Regulation Board

Purpose: Test that battery voltage can be regulated and supplied to all system components

Method: Connect battery through Power Regulation Board and to oscilloscope to verify correct output voltages. Then connect to each system component, verify that the components work as intended (i.e. Pixy sends MCU correct data, motors spin as intended etc.)

Risk Reduction: Ensures that all components will function correctly, and also reduces the risk of incorrect input voltages or current surges, reducing risk of component damage.

Equipment: LiPo battery, Power Regulation Board, oscilloscope, every other system component

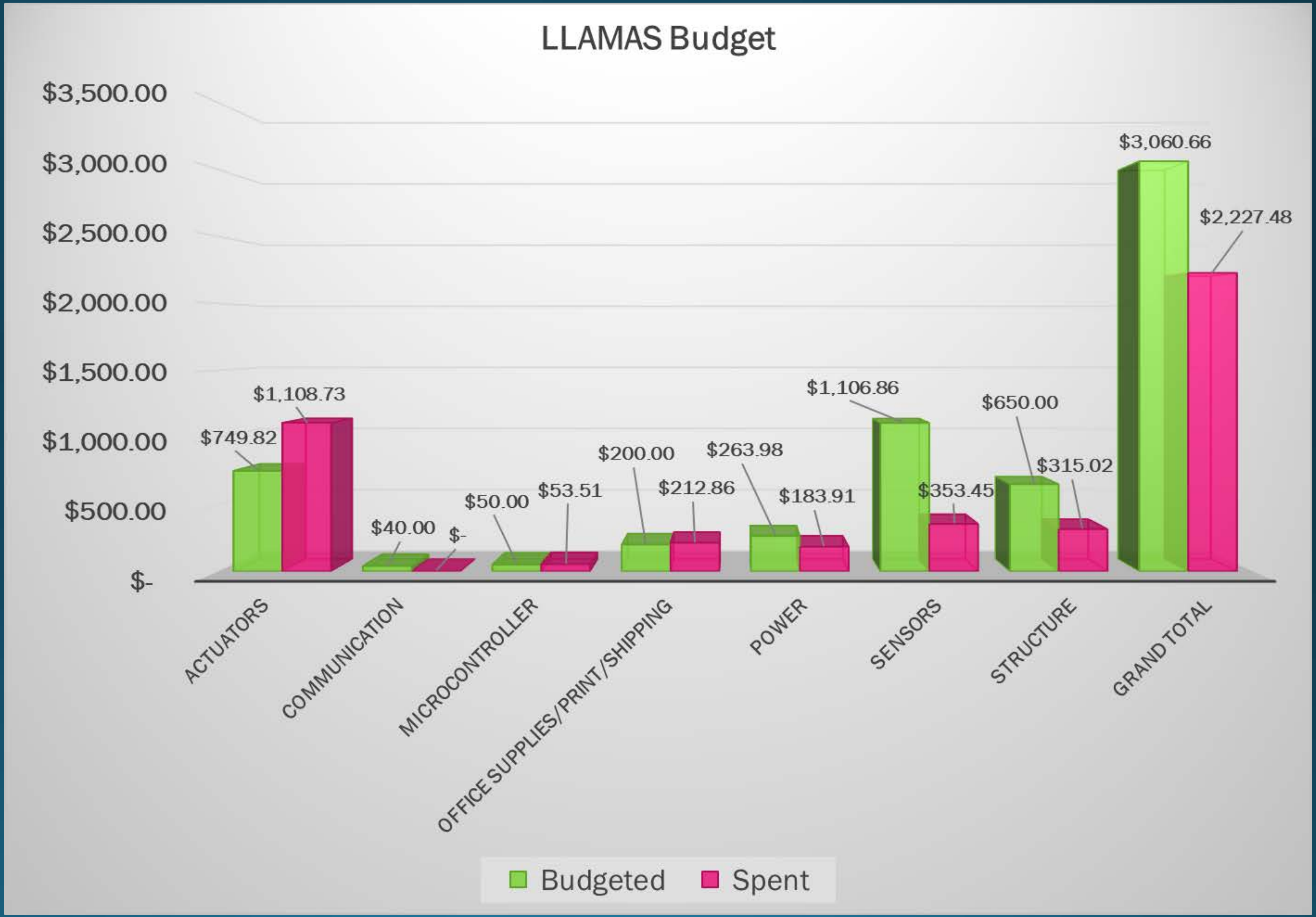
Note: 5-10 hours left till completion.

Results: Verified correct output voltages using oscilloscope on current revision of board (unit tested), will be fully completed with other system components when second revision arrives (no general circuitry changes, only changes to board size, mounting holes, easier component attachment sections etc.)

Budget

Budget

- Discrepancies derive from:
  - Purchase of extra motors to test two different families of motors
  - Lack of communication purchase
- Buying down risk of certain components
  - Motherboard
  - Motors



Budget – Procurement

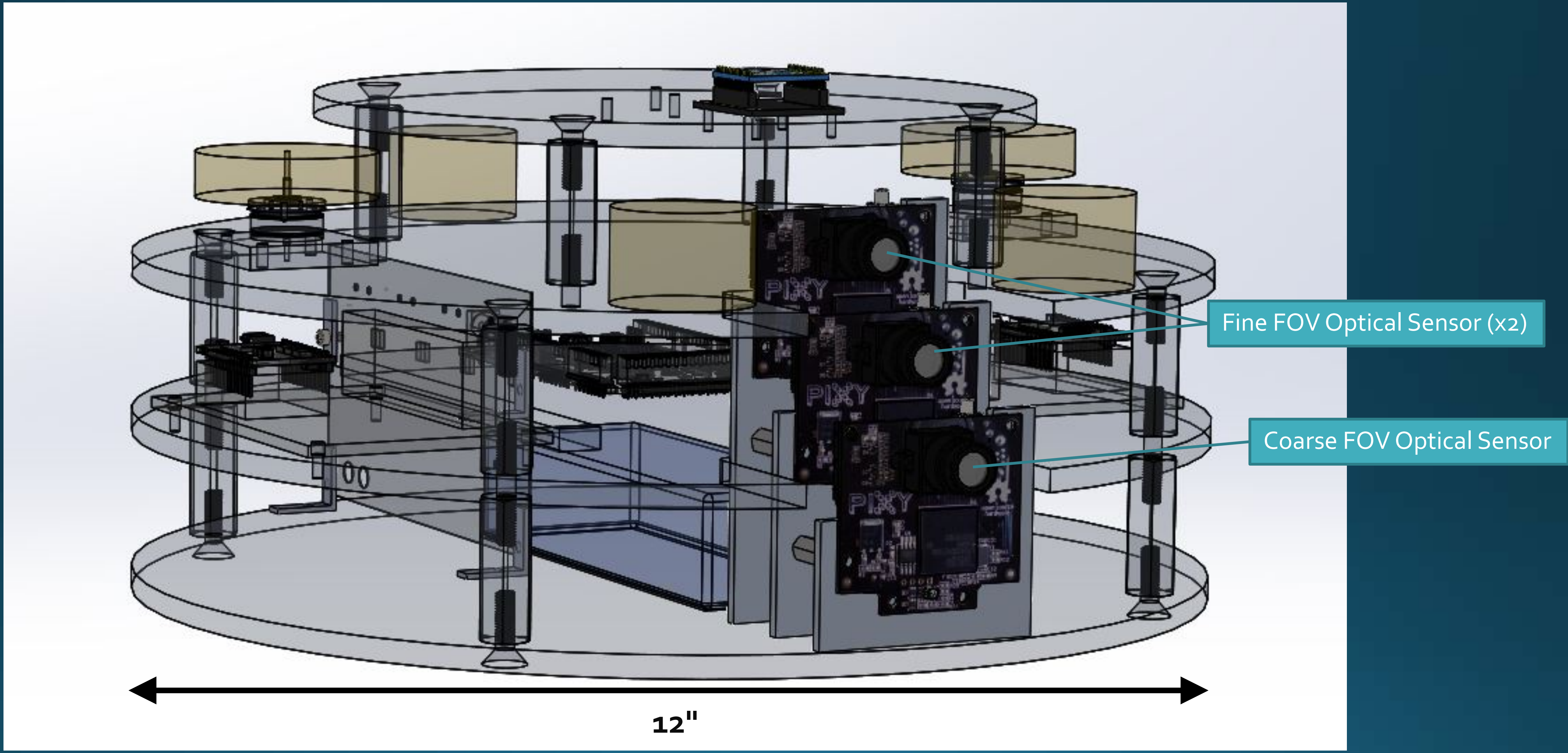
Subsystem	Items on Hand	Outstanding
ADCS	Pixy Camera (3), Lens (2) Motor (2), Motherboard (2), Controller (2) Encoder (2)	Pixy Camera (1), Lens (2) Motor (2) Encoder
CDH	Microcontroller Xbee (2)	
EPS	Battery PCB (resistors, capacitors) DC/DC Converter (2) Voltage Checker, Voltage Alarm	PCB (rev 2) Arduino Shield Electronic components Xbee breakout board (2)
Structures	Aluminum (6) Standoffs	

Questions

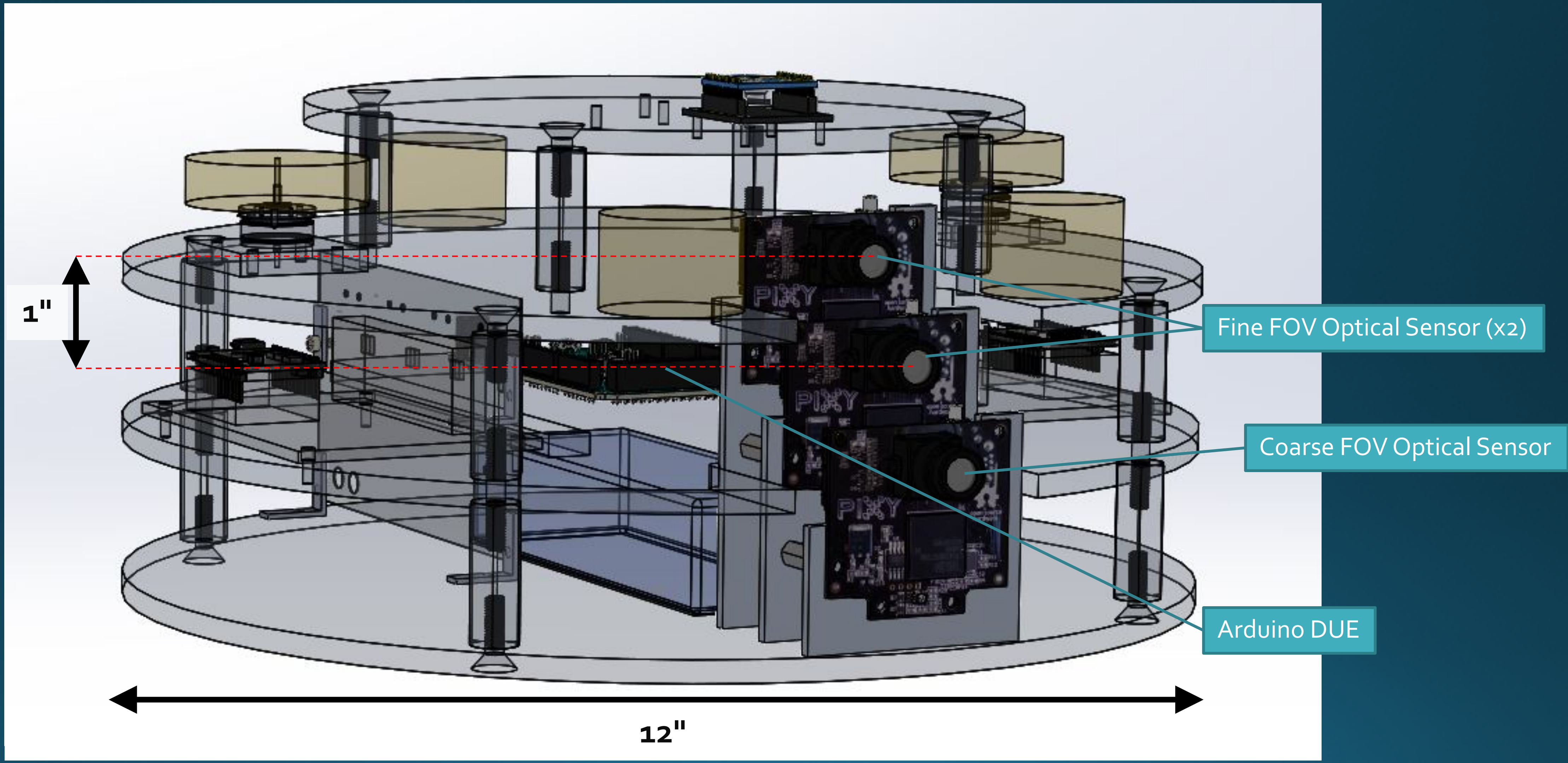
Backup Slides

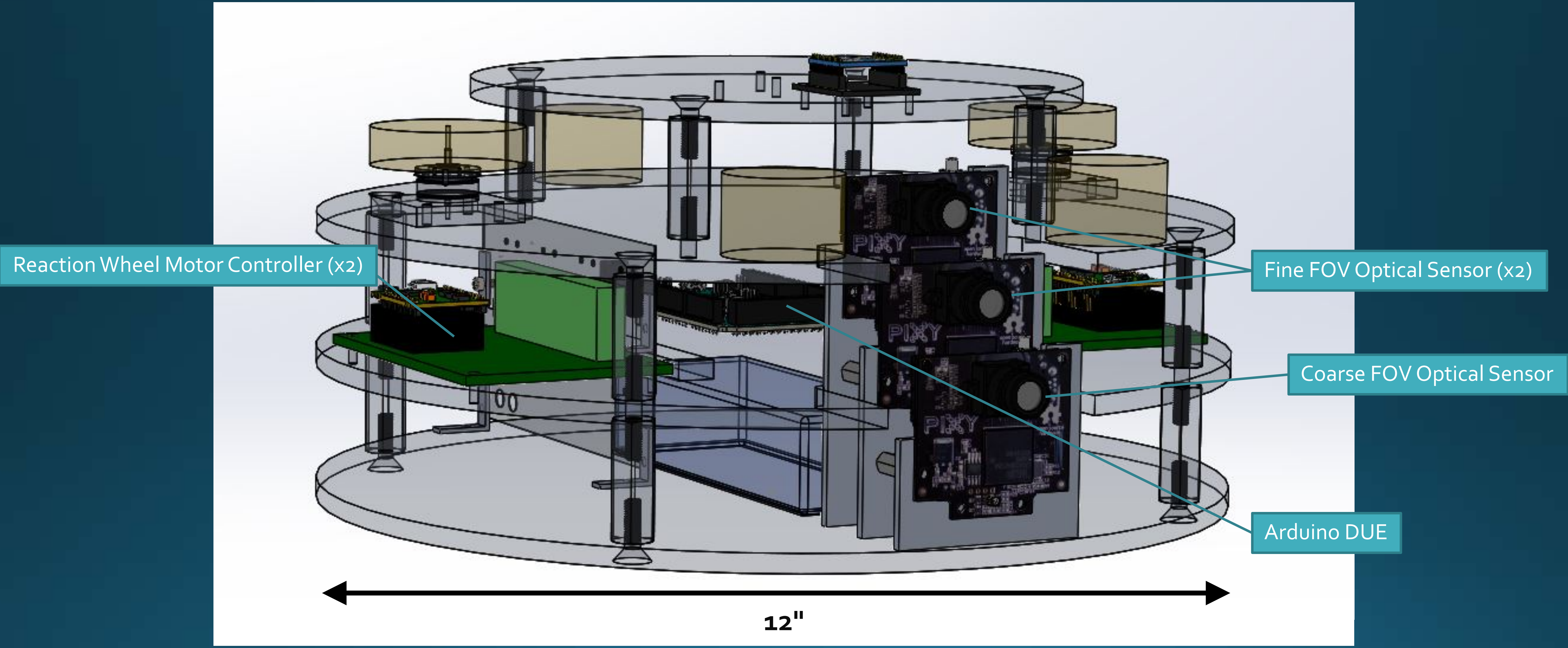
TestTable

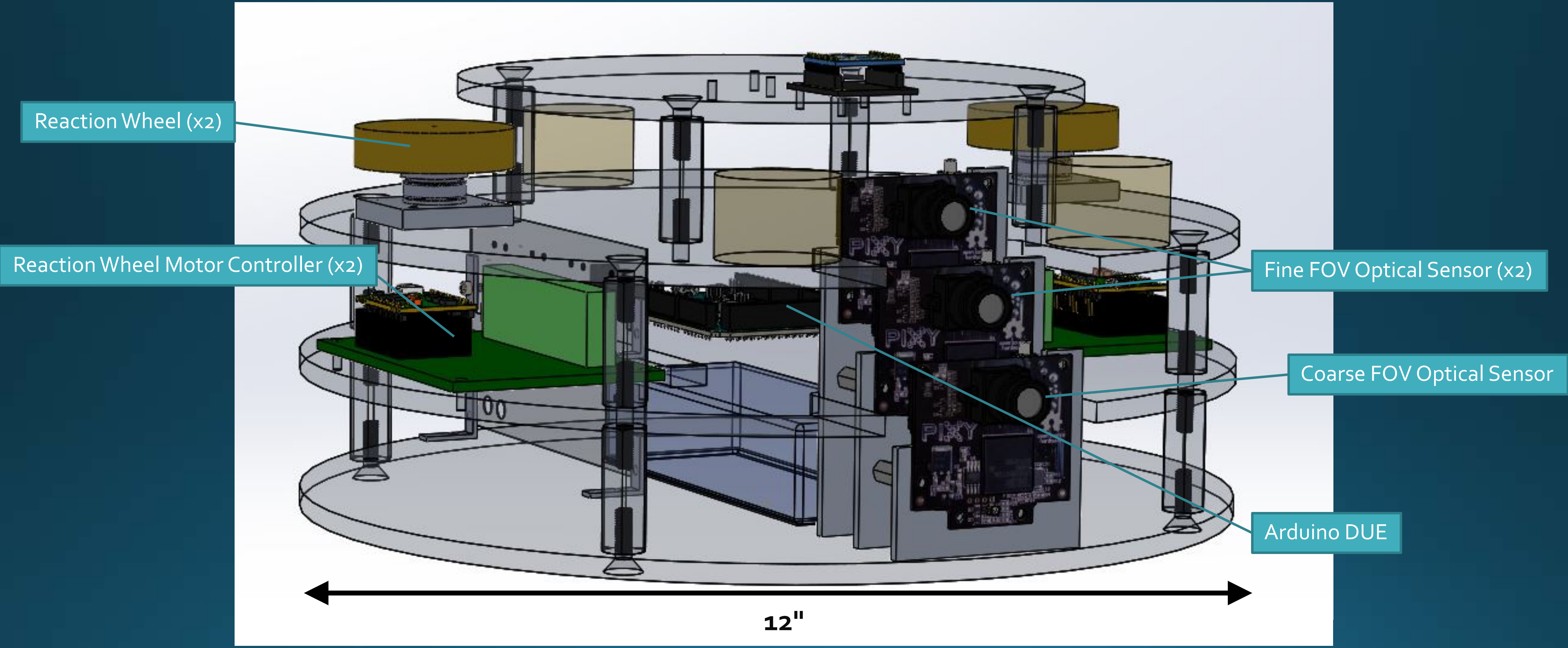
- **Functional Requirement 1** - The TestTable shall allow for two degrees of freedom in translation and one in freedom of rotation in a low friction environment.



Fine FOV Optical Sensor (x2)
Coarse FOV Optical Sensor
12"


1"
Fine FOV Optical Sensor (x2)
Coarse FOV Optical Sensor
Arduino DUE
12"


Reaction Wheel Motor Controller (x2)
Fine FOV Optical Sensor (x2)
Coarse FOV Optical Sensor
Arduino DUE
12"


Reaction Wheel (x2)
Reaction Wheel Motor Controller (x2)
Fine FOV Optical Sensor (x2)
Coarse FOV Optical Sensor
Arduino DUE
PIXY
PIXY
PIXY
12"

Structures – Full Hardware Integration

Purpose: To ensure everything fits properly and verify all mounting holes and hardware have been designed properly

Equipment: All subsystem components and structural hardware

Results: (Expected)

- Everything integrates properly and there are no physical interference issues
- Routing holes for wires can be finalized

Structures – Center of Mass Test

Purpose: To experimentally locate the fully integrated MockSat center of mass
Determine the final placement of the mass balance system to align MockSat center of mass with axis of rotation

Equipment: Fully integrated MockSat with mass balance system machined

Results: (Expected)

- Initial center of mass and axis of rotation will not be aligned
- Once mass balance location has been adjusted CoM and axis of rotation will be aligned

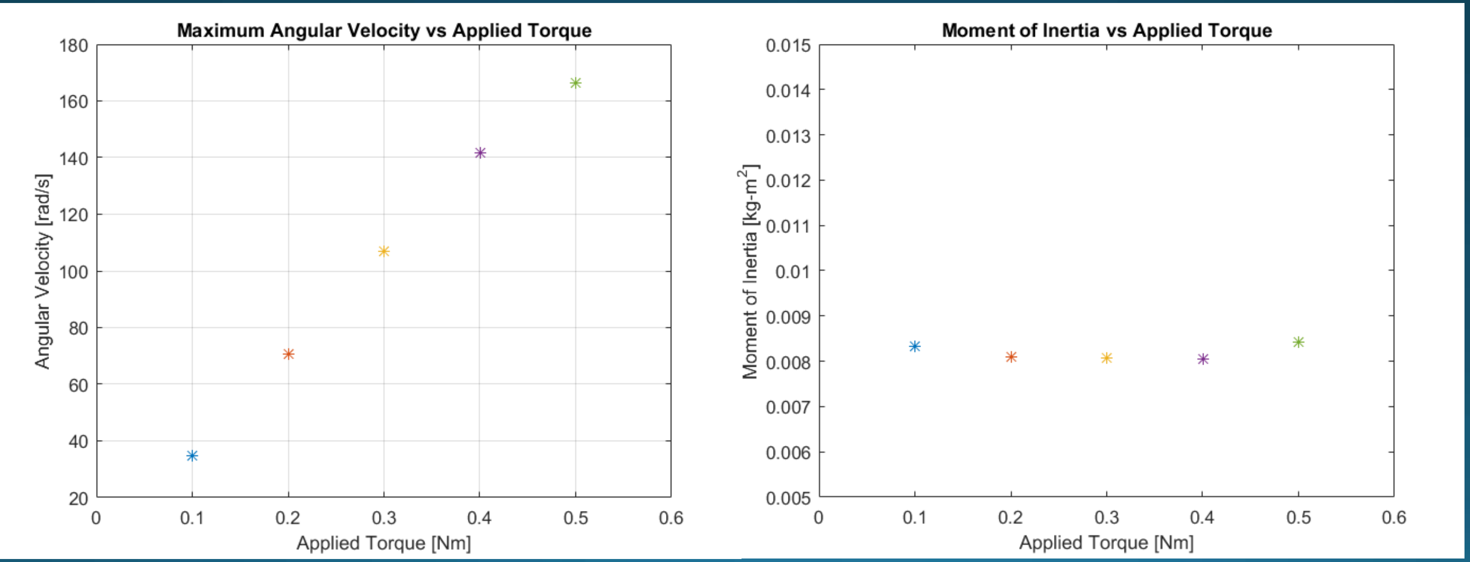
Structures – Moment of Inertia Test

Purpose: Experimentally determine actual MockSat moment of inertia about axis of rotation

Equipment: Fully integrated and balanced MockSat, integrated encoder with station keeping apparatus, ability to control MockSat rotation with reaction wheels

Results: (Expected)

- Moment of inertia will be backed out by recording motor torque and MockSat angular position over time with encoder



Data from ASEN 3200 Lab

ADCS – Encoder Unit Testing

Purpose: Demonstrate ability of encoders to determine relative pointing of MockSat and reference target for V&V

Method: Use demo board for manufacturing calibr

Risk Reduction: Ensures selected lens meets required pointing accuracy with smaller CMOS then designed for. Reduces development time for final testing environment.

Equipment: Pixy camera, target source (lightbulb), PixyMon software, measurement device (yardstick)

Note: Since there is such a large margin in both fine and coarse sensor performance vs. the requirements, the level of detail in the characterization does not need to be precise (i.e. distance measurements with an accuracy of 1/16" is sufficient)

Results: Average loss from advertised horizontal FOV to actual FOV ~40%. Vertical FOV is ~60% of horizontal FOV. This allows for accurate modeling and selection of target motion to remain within view of the Pixys.

25%	50%	75%	95%

Coulomb Friction Characterization

Duty Cycle (%)	Input Current (Amps)	Output Current (Amps)	RPM
80	0.0167	0.0167	1039-814
70	0.0163	0.0163	733-456
65	0.0161	0.0161	652-338
60	0.0159	0.0159	530-225
58	0.0158	0.0157	814-475
55	0.0157	0.0157	587-270
52	0.0155	0.0155	0

Conclusions: Initial Coulomb friction is calculated to be 0.1303 ±0.0001 mNm. At low applied currents wheel speed is highly variable, and it seems to be difficult for the motor controller to operate consistently.

Recommendations: We should operate the motor in one direction only. Precisely commanding the motors at very low speeds is nearly impossible. Additionally, Coulomb friction is larger than the anticipated torque required.

EPS – Battery

Purpose: Test battery to ensure a system run time of at least 1 hour

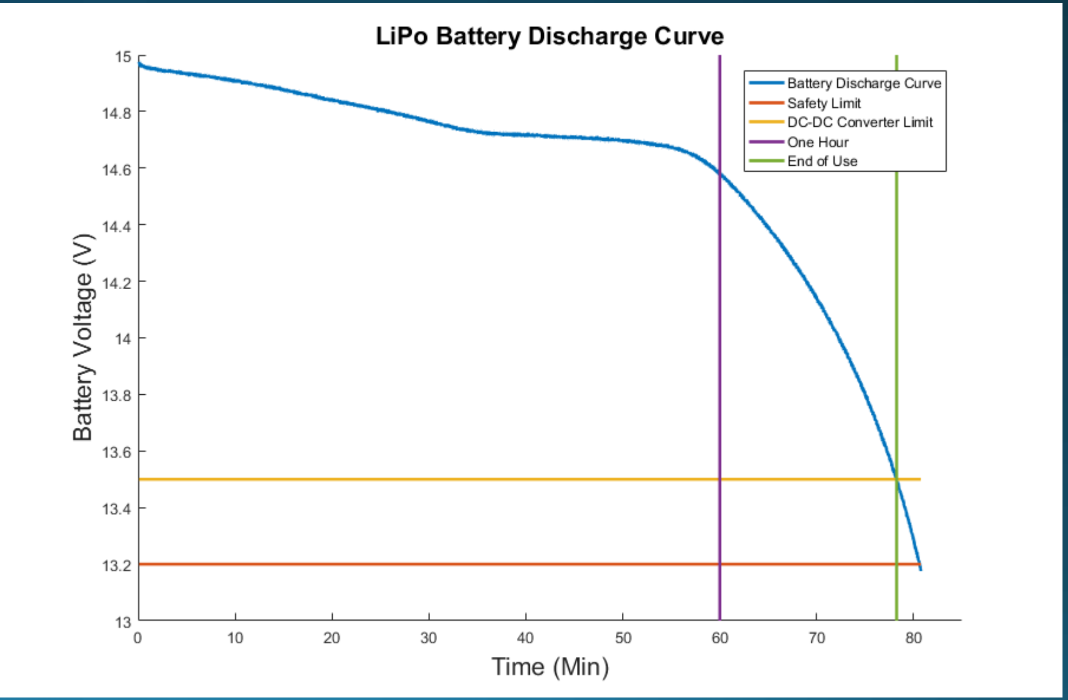
Method: Discharge battery through a power resistor at currents that are representative of expected system limits (~0.75 A), measure voltage drop over time

Risk Reduction: Ensures battery safety, as well as testing time goals

Equipment: LiPo battery, power resistor, voltage DAQ, computer with LabView

Note: Expected system current as predicted from component data sheets and power budget

Results: Battery voltage in acceptable range >1 hour



CDH – UART to XBee

Purpose: Determine communication limitation between MCU and ground station. The desired data throughput is 8.4 kbps, while the

Method: Send simulated telemetry data from Xbee on MockSat to Xbee connected to ground station MyRio. Confirm accuracy of received data to transmitted data.

Risk Reduction: If the desired data throughput cannot be reliably met, the ground station will just have to reduce the rate at which data is sent to the ground station from 10 Hz to 5 Hz or less.

Equipment: Arduino Due, Xbee (2), ground station

Note: The Xbee communication has already been implemented in the 3200 spin modules, which our project draws heritage from. The limitations regarding how much data can be reliably transmitted per second has yet to be determined.