Astrobee Systems Engineering

Design Overview

Systems Engineering Team

- Jonathan Barlow (ARC-TI)
- Maria Bualat (ARC-TI)
- Estrellina Pacis (ARC-TI)
- Hugo Sanchez (ARC-RE)
- Trey Smith (ARC-TI)
- Allison Zuniga (ARC-TI, alum)

Fault Management - Drivers

- Crew rescue is possible in case of serious failures
- Shutting down completely does not cause loss of mission
- Crew can repair damage, assuming proper design (serviceable modules, on-orbit spares, etc)

Fault Management - Approach

- Triage faults by severity and frequency
  - Avoid investing any effort mitigating low-severity low-frequency faults
- When possible, design to eliminate fault cause rather than developing responses
  - Make system simpler, not more complicated
- Respond to faults at integrated system level
  - Allows coordinated response across multiple subsystems
  - Occasional exceptions when fast "reflex response" is needed
- Generally fail safe

Fault Management - Responses

- Fail Operational
  - Safe Return: Autonomously return to dock if needed (such as low battery and operator out of contact)
- Fail Safe
  - Safe Stop: Halt motion and station keep
  - Safe Terminate: Disable propulsion system (drift)
- Reset hardware or software services that are not responding
- Mark specific hardware or software services inoperable, disabling relevant commands
  - Also covers intentional hardware configuration changes

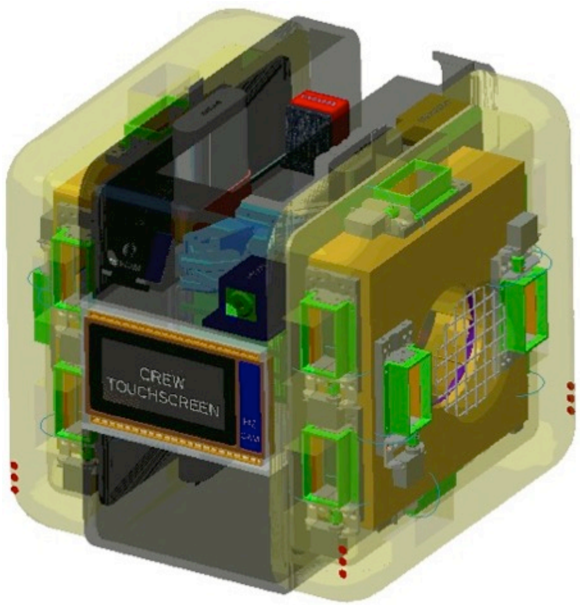
Fault Management - Out of Scope

- Recovery from mobility hardware failures
  - Minimize component count and use reliable components
  - Use Safe Terminate on component failure
  - Avoid implementing GN&C for various degraded hardware states (hard)
- Automated path planning around obstacles
  - Use Safe Stop mode instead, let operator figure out what to do next
- Substantial crew interaction
  - Use signals to indicate robot intention (always, no need to detect crew member presence)
  - Obstacle avoidance will treat crew like any other object (static obstacle)
  - No modeling of crew motion or "robotic etiquette"
- **All of these are great topics for guest scientists to investigate after Astrobee is operational**

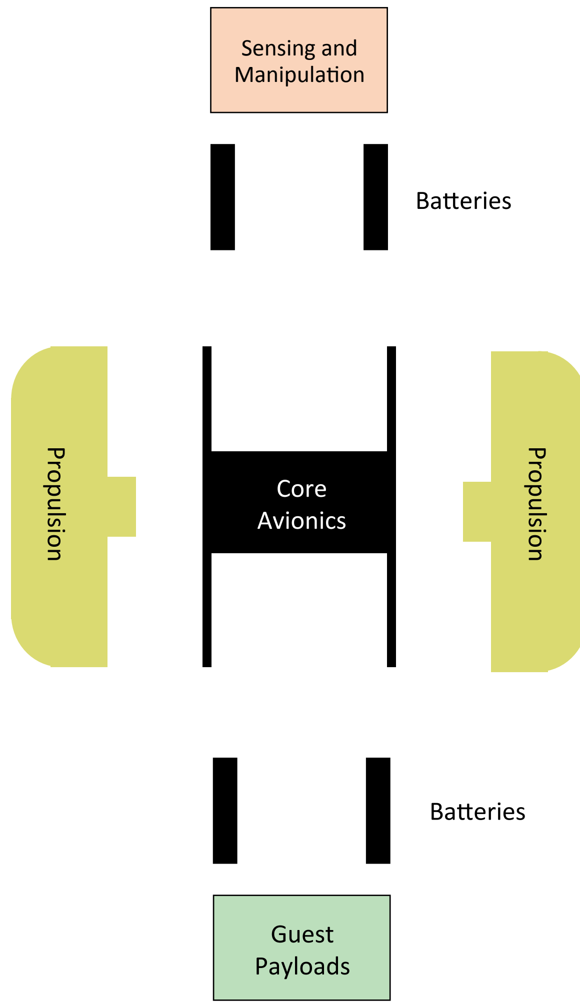
Technical Performance Measures (TPMs)

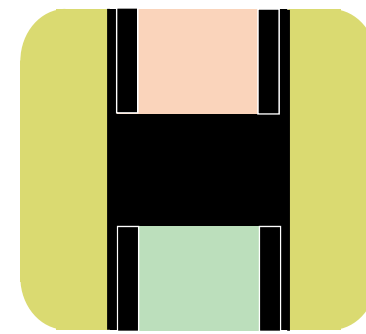
- Projected performance numbers we can compute and recompute as we proceed through the development process, to track project health
- Selected measures:
  - Mass
  - Noise at max thrust
  - Flight time
  - Standby time
  - Localization error (linear and angular)
  - Pose control error (linear and angular)
  - Navigation mean time between failures
- Will report baseline assessment of TPMs at PTR2
  - Will need subsystem help to run assessment

Basic Packaging



FORWARD

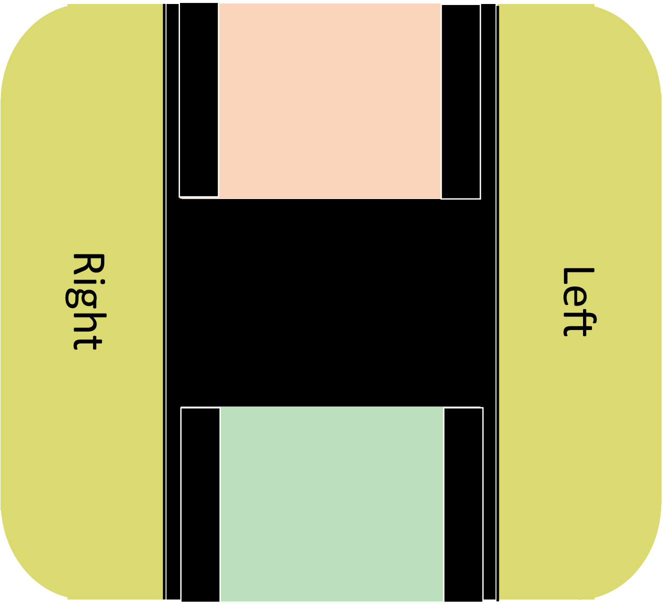




FRONT VIEW

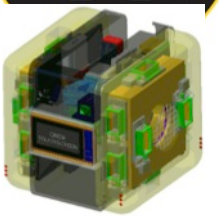
Or More Poetically

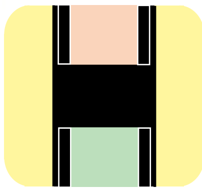
"Sideways Hamburger"



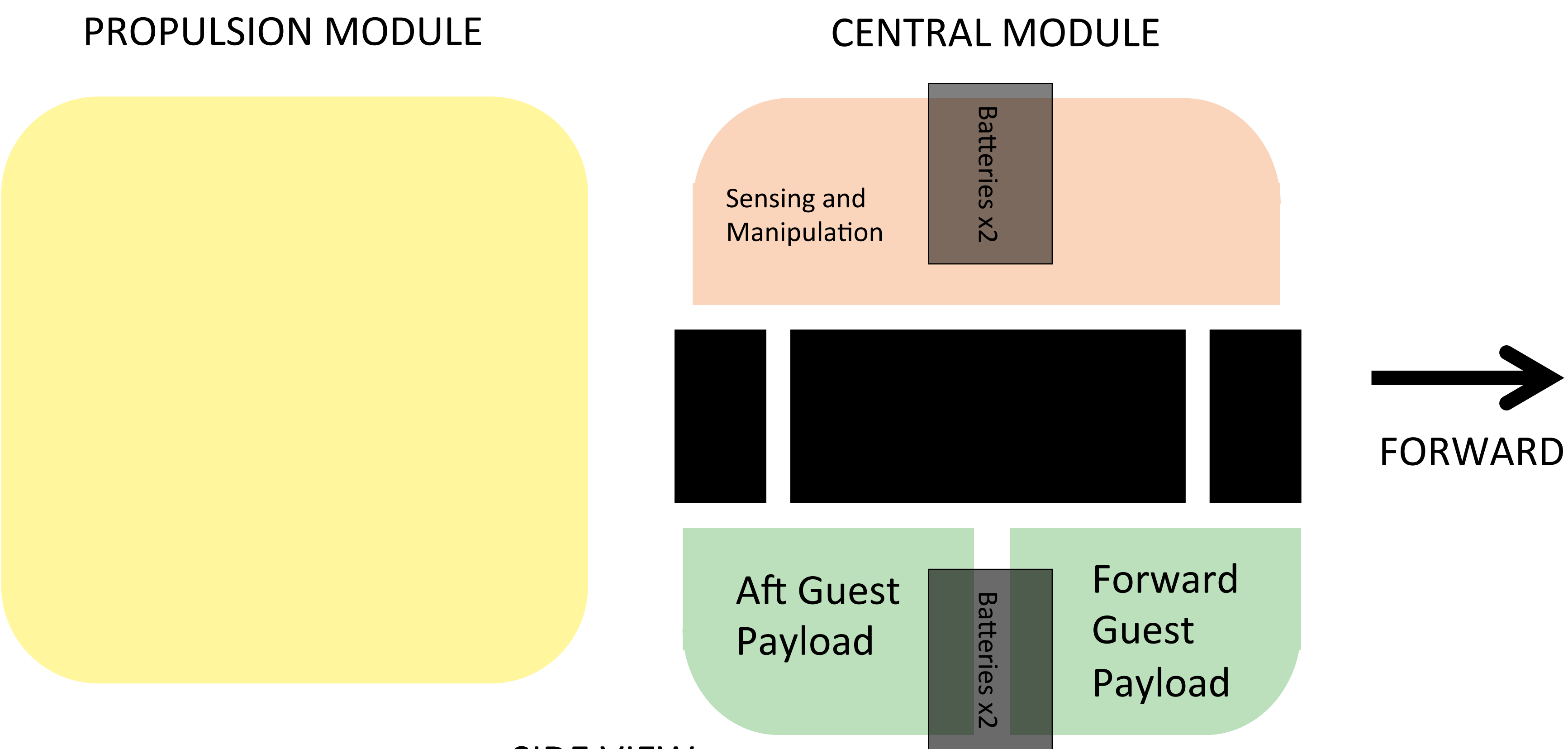
FRONT VIEW

Basic Packaging



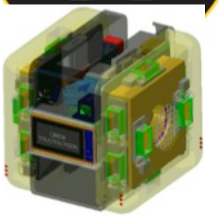


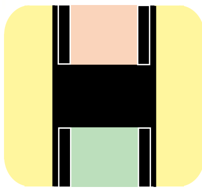
FRONT VIEW



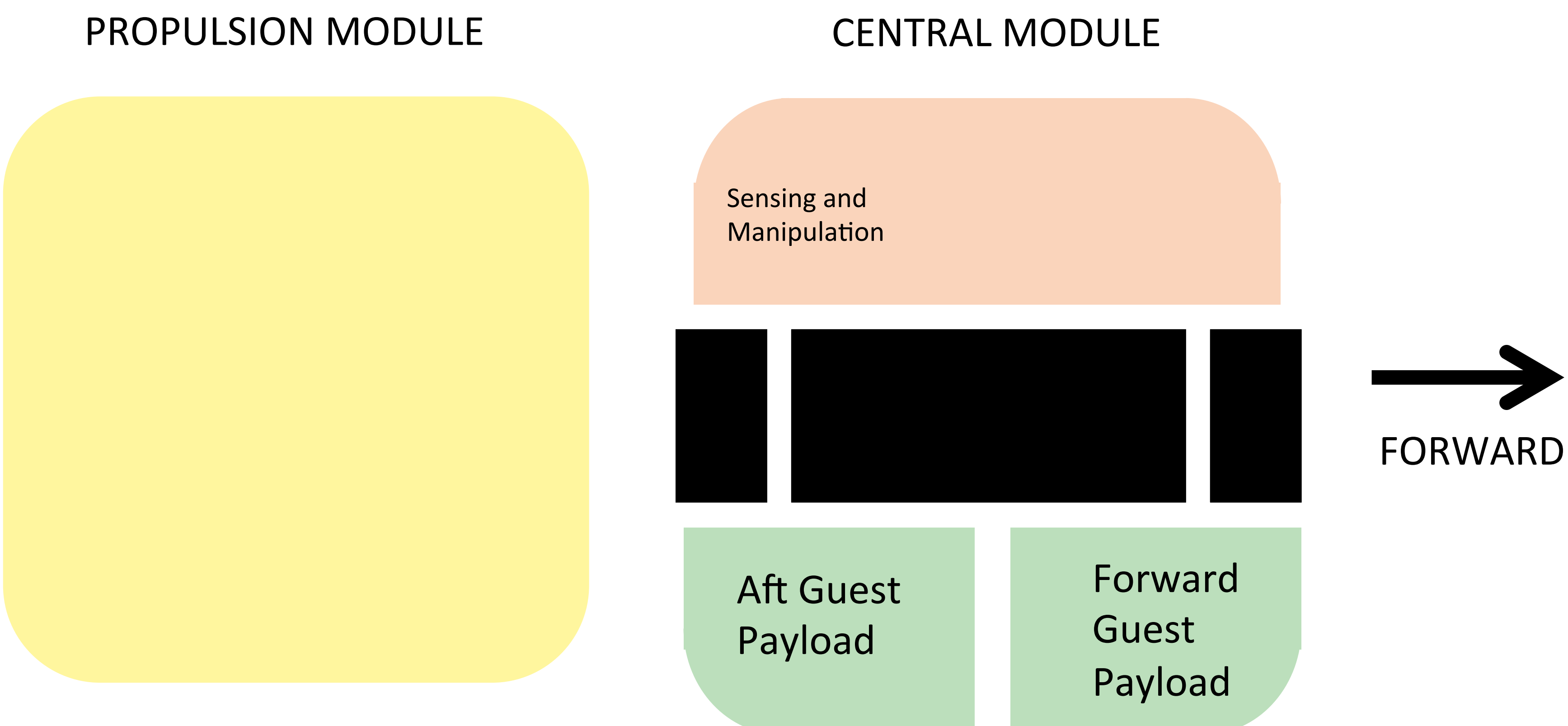
SIDE VIEW

Basic Packaging



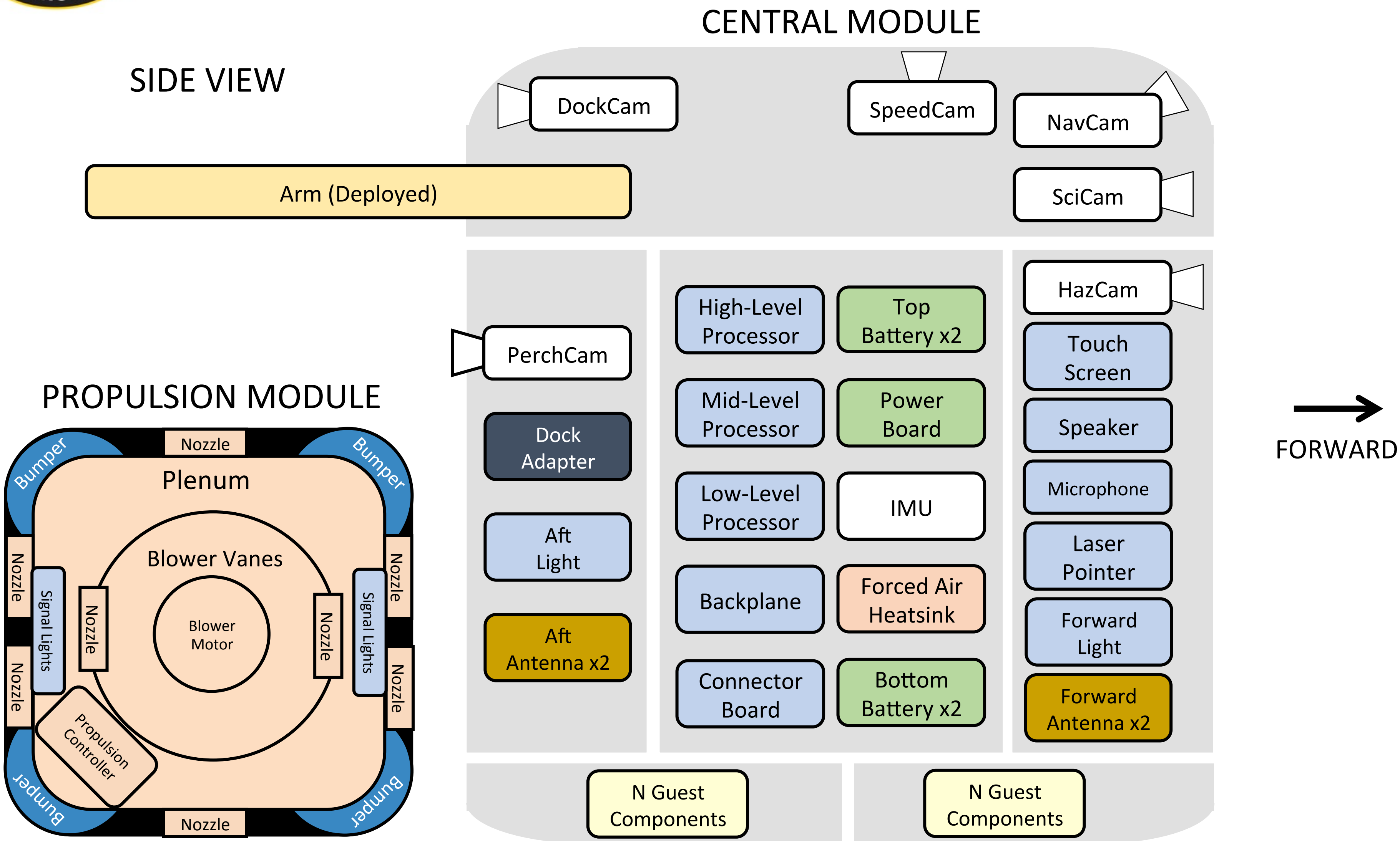


FRONT VIEW



SIDE VIEW

Robot Architecture



Astrobee Structure Subsystem

Design Overview

Subsystem Team

- Earl Daley (ARC-RE, Lead)
- Jeff Blair (ARC-RE)
- Troy Shilt (ARC-RE, Intern)
- Hugo Sanchez (ARC-RE)

Design Drivers

- Mass
  - 6kg for entire system
- Modularity
- Sensor geometry
- Loads
  - Launch
  - Max velocity impact
  - Crew kick

Trade Study

Attributes	Options
Fastening mechanism (TBD)	• Capture screws • Latches • Hinge pins
Material	• Aluminum • Ultem

Selected Design

- Aluminum structure
  - Pros: strong
  - Cons: requires machining
- Capture Screws
  - Pros: can be used at all module levels
  - Cons: requires tools

Modularity

1	2	3	# Per Parent	Crew Replaceability
Free Flyer			2	
	Central Module		1	[Base]
		Core Module	1	[Base]
		Battery	4	Very Easy
		Forward Module	1	Easy
		Aft Module	1	Easy
		Top Module	1	Easy
		[REALM Reader]	1	Very Easy
	Propulsion Module		2	Easy
		Propulsion Module Structure	1	[Base]
		Propulsion Module Wiring	1	Not required
		Propulsion Avionics Package	1	Not required
		Bumpers	4	Moderate
		Impeller	1	Moderate
		Nozzles	TBD: 6-8	Moderate
		Signal Lights	2	Moderate
		[REALM Reader Antenna]	1	Very Easy

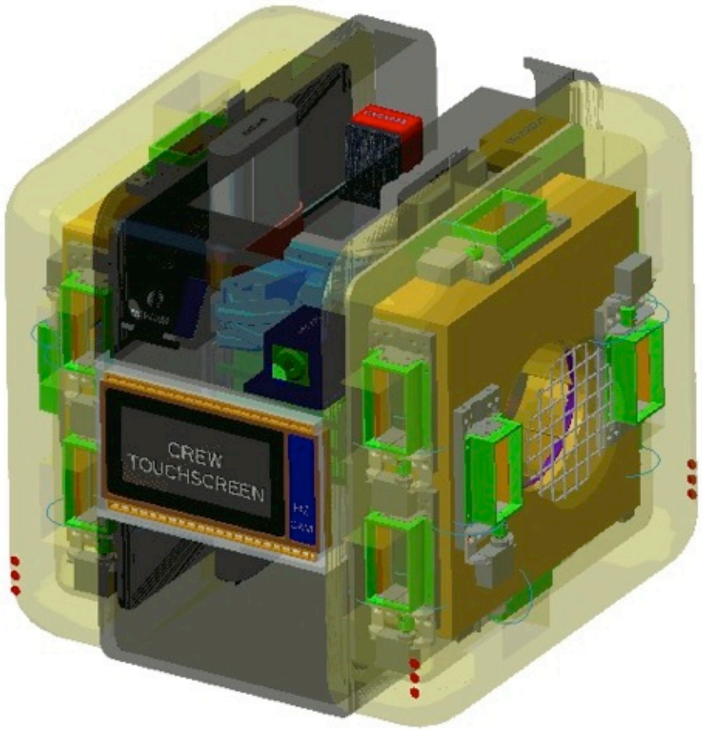
Complete breakdown is on SVN - TBD

Geometry

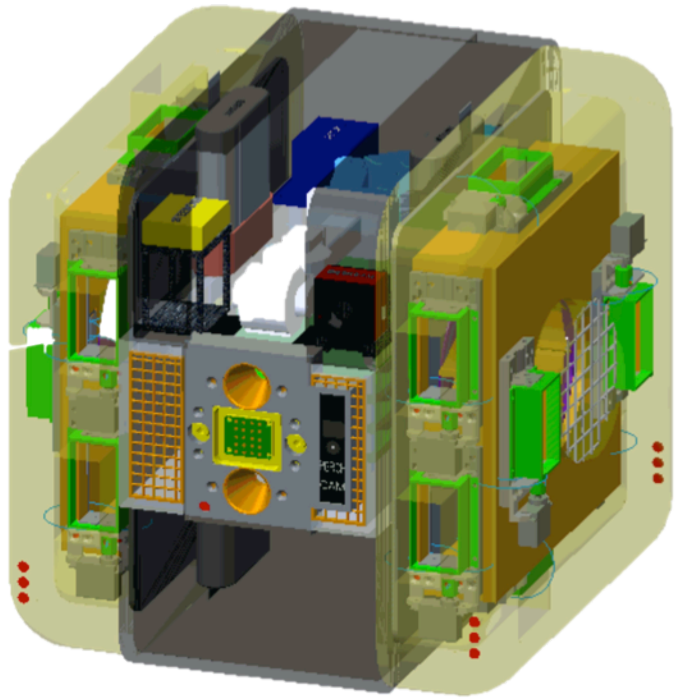
Name	Geometry Requirements	Location
NavCam	Camera axis shall be pitched upward 30 degrees relative to forward motion direction; FOV shall be 90% clear	Forward Top Bay
SciCam	Camera axis shall be aligned with forward motion direction; FOV shall be 100% clear	Forward Top Bay
Crew Touch Screen	Crew member with face in view of payload camera should be able to use the touch screen dispay effectively	Forward Top Bay
HazCam	Camera axis shall be aligned with forward motion direction; FOV shall be 90% clear	Forward Face
Perching Arm	Shall be able to point SciCam in pan/tilt axes with arm motion	Aft Top Bay
DockCam	During docking final approach, shall have at least one entire docking target in view (targets in neighborhood of dock, location somewhat flexible). FOV should include deployed arm end effector, and portions of handrail and wall, during perching final approach.	Aft Top Bay
PerchCam	Sensor effective volume shall include deployed arm end effector, and portions of handrail and wall, during perching final approach. Effective volume defined by FOV and effective range constraints; may require standoff due to minimum range constraint.	Aft Top Bay
Dock Adapter	Dock adapter should be on face to make best use of space (stick out less from wall)	Aft Face
SpeedCam	Camera axis shall be aligned with nominal "up" direction (usually pointing toward overhead); FOV shall be 100% clear	Forward Top Bay

Original list is on SVN - TBD

Drawing



Forward Top



Aft Top

Astrobee Propulsion Subsystem

Design Overview

Subsystem Team

- Blair Mclachlan (ARC-AOX, Aero Lead)
- Mike Mcintyre (ARC-RE, GNC Lead)
- Jesse Fusco (ARC-RE)
- Earl Daley (ARC-RE)
- Jeff Blair (ARC-RE)
- Brian Koss (ARC-RE)
- Troy Shilt (ARC-RE, Intern)
- John Love (ARC-RD)
- Hugo Sanchez (ARC-RE)
- Travis Mendoza (ARC-RE, Intern)

Design Drivers

- Thrust
  - 0.3 Newtons on all axes
  - 0.6 Newtons on one axis
- Noise
  - 65dBA maximum
  - <60dBA preferred
- Volume
  - 3inch module thickness
- Power
- Mass

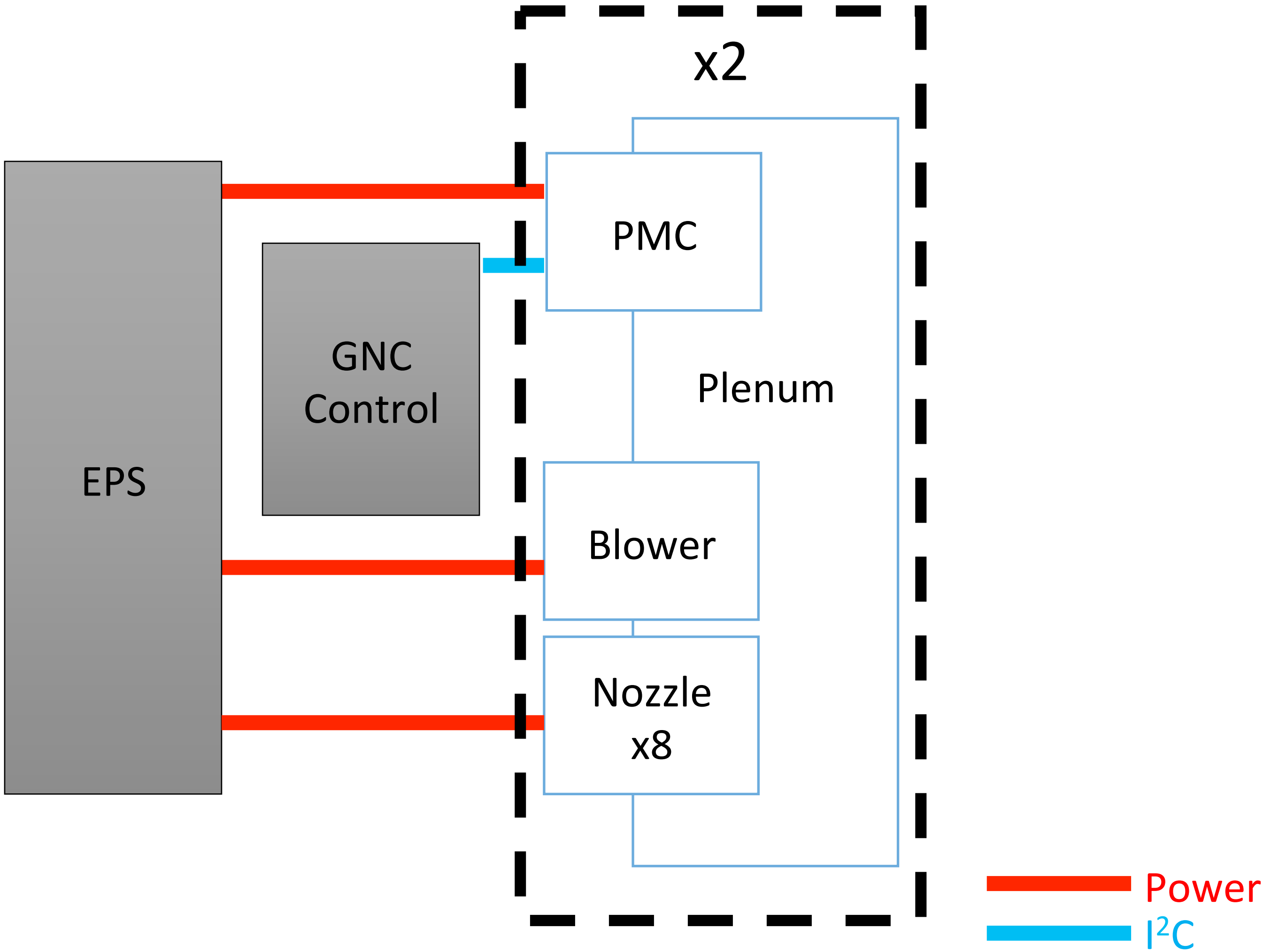
Trade Study

Attributes	Options
Propulsion type	• Axial fan • Compressed air • Blower system
Blower diameter	• 4, 4.4, 4.6, and 5 inch
Blower height	• 2 inch • 1 5/8 inch
Nozzle flapper	• Single flapper • Double flapper
Nozzle open area	• 2 cm^2 • 4 cm^2
Nozzle efficiency	• Guillotine • Flapper

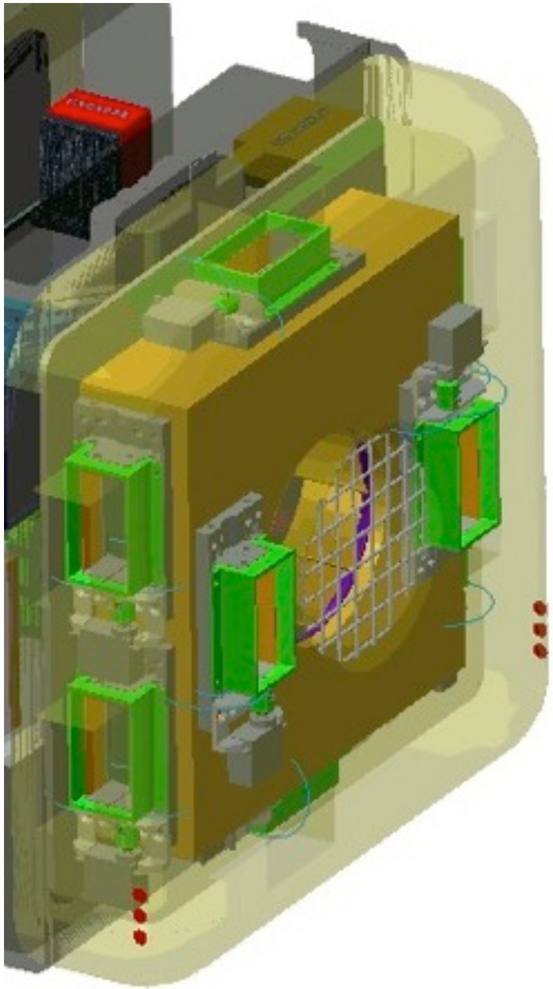
Selected Design

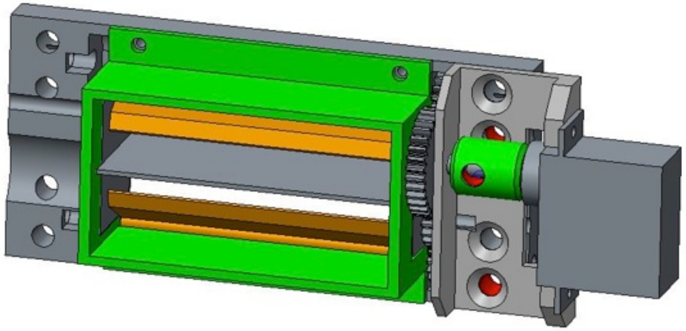
- Two blower propulsion modules
  - Pro: Packaging is more simple than axial fan design
  - Con: Blower noise is expected to be higher than axial fans
- Blower with 5" Diameter and 1 5/8" Height
  - Pro: Larger blower allows RPM and SPL
  - Con: None known - limited by volume constraints
- Dual Flapper Nozzle
  - Pro: Shorter in height and >0.9 efficiency
  - Con: More complex gearing for single servo
- 8 nozzle design
  - Pro: Nozzles are farther apart (less coupling)
  - Con: Limits blower size and nozzle size

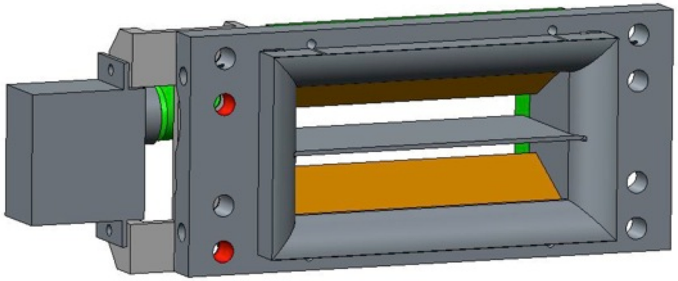
Architecture Diagram



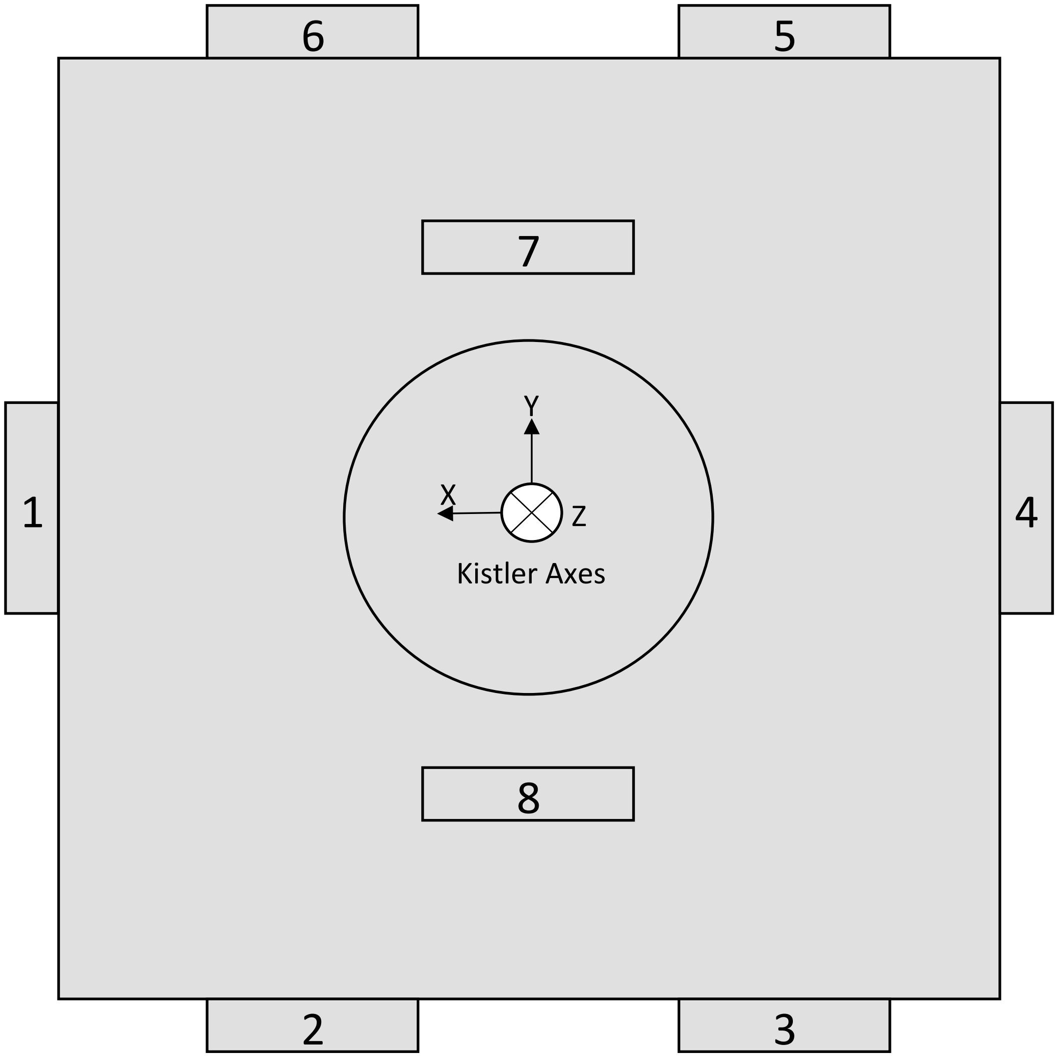
Drawing







Layout



Pure Force or Moment Axis	Nozzles Required
+Fx	4
-Fx	1
+Fy	2,3
-Fy	5,6
+Fz	7,8
-Fz	NA
+Mx	7
-Mx	8
+My	NA
-My	NA
+Mz	2,5
-Mz	3,6

Component List

Component	Quantity
Nozzle Body	16
Nozzle Flapper	32
Nozzle Gears	64
Nozzle drive shafts	32
Servos	16
Blower	2
Blower Adapter	2
Plenum	2
Motor	2
Motor Plate	2

Astrobee CDH Subsystem

Design Overview

Subsystem Team

- Dmitriy Arbitman (ARC-RE)
- Steve Battazzo (ARC-RE)
- Jon Dewald (ARC-RE)
- Brandon Gigous (ARC-TI, Intern)
- Jason Lum (ARC-TI)
- Nghia Mai (ARC-RE)
- In Won Park (ARC-TI)
- Jongwoon Yoo (ARC-TI)
- Shang Wu (ARC-RE)
- Vinh To (ARC-TI)

Design Drivers

- Low power consumption
- High computing power
- Multiple processors
- Small form factor
- Low mass
- Support multiple payloads
- Modular

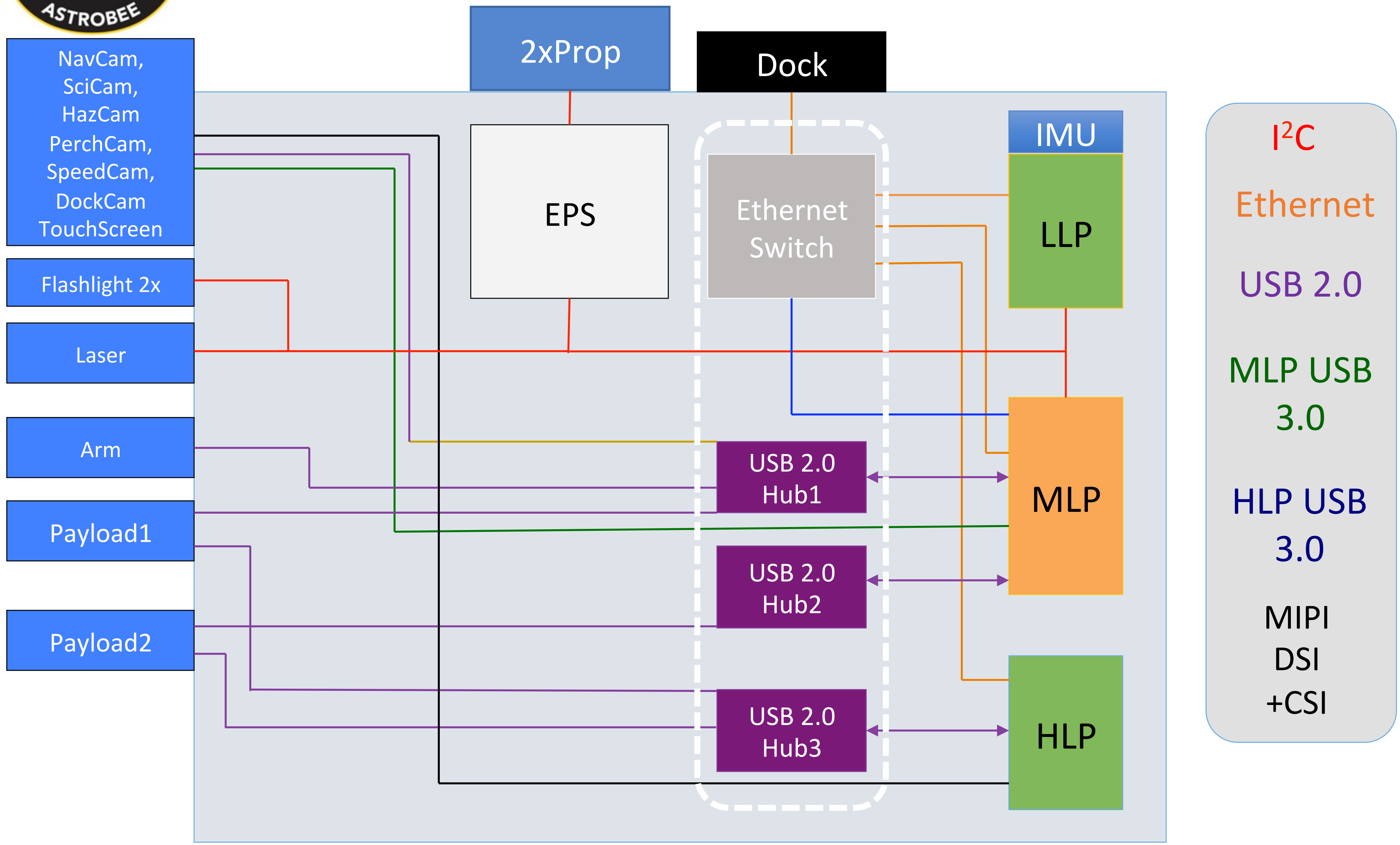
Trade Study

- Arm vs x86
- Exynos vs OMAP vs i.MX6 vs SnapDragon
- Single vs dual vs quad cores
- SOM and SBC HW
- Wide variety of comm support
- Custom carrier boards

Selected Design

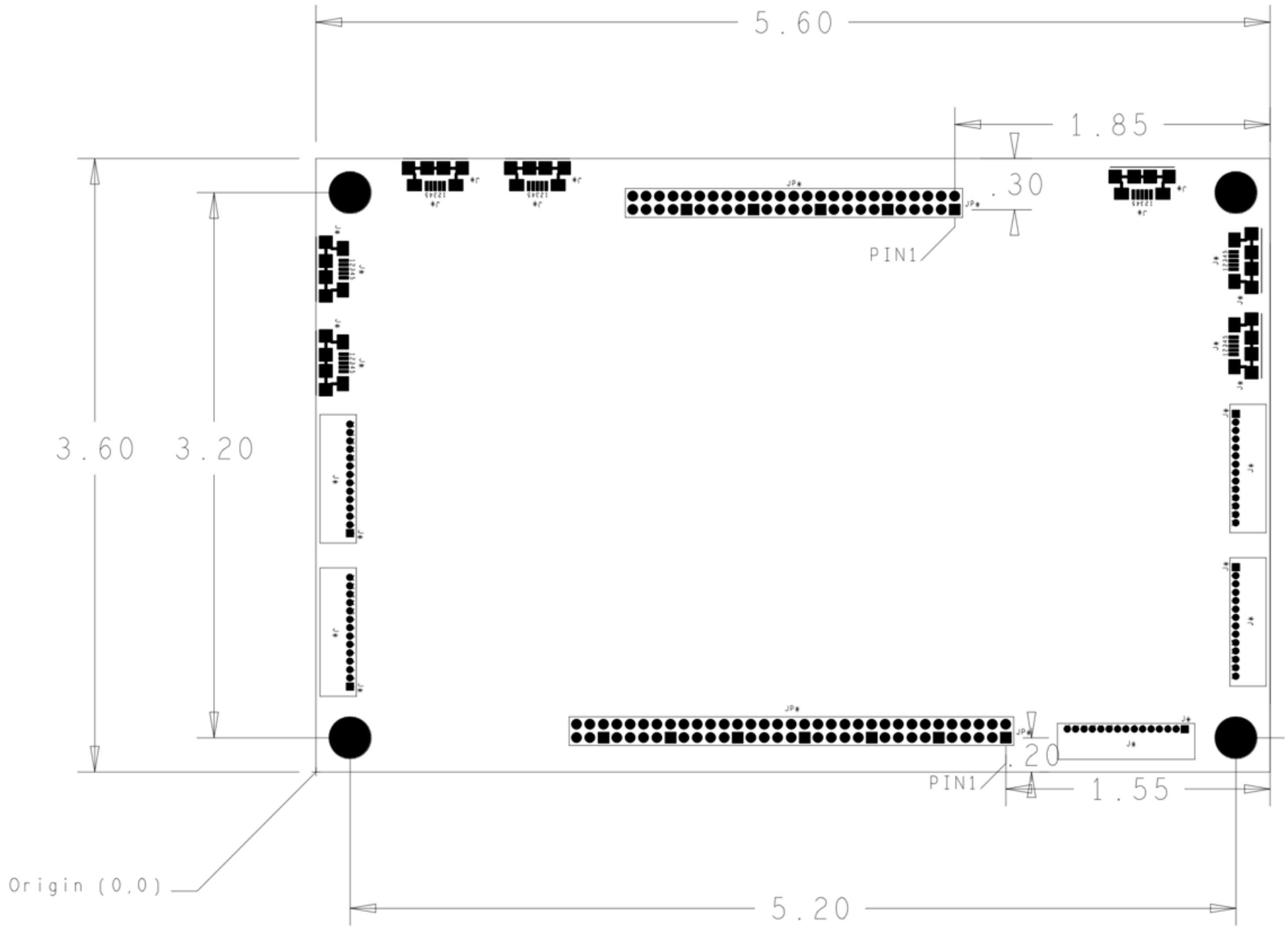
- Low Level Processor (LLP) – ***Wandboard Dual***
  - Dual core i.MX6 (ARM Cortex-A9, ARMv7 32-bit)
  - 1 GB RAM
  - 3 x I^2C bus
  - SPI
  - GPIO
- Middle Level Processor (MLP) & High Level Processor (HLP) – ***IFC6501***
  - Quad core Snapdragon 805 (ARM Cortex-A15 class, ARMv7 32-bit)
  - 2GB RAM
  - 2 x I^2C bus
  - 1 x USB 3.0
  - 2 x USB 2.0
  - MIPI DSI + CSI
  - GPIO

Architecture Diagram



Avionics Stack – Side View

Avionics Stack – Top View



Component List

- Backplane
- LLP carrier board
- MLP + HLP carrier board
- Touchscreen
- Peripheral Bay Connector
- LED signal indicator
- Laser pointer
- LED flashlight

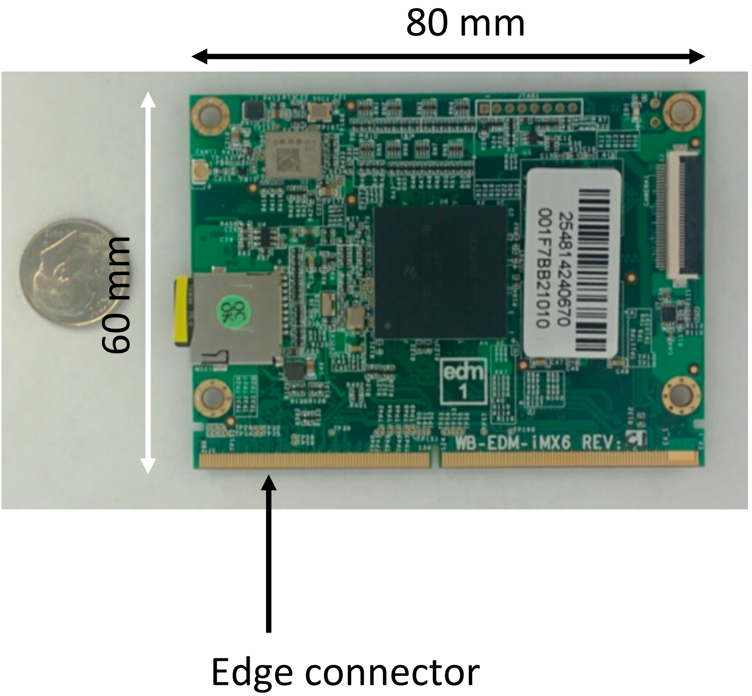
Backplane Board

- Connect EPS, LLP, MLP, and HLP
- 5-port 100 Mbit network switch
- 1 x 4-port USB 2.0 hub and 1 x 7-port USB 2.0 hub for MLP
- 1 x 4-port USB 2.0 hub for HLP

LLP Trade Study

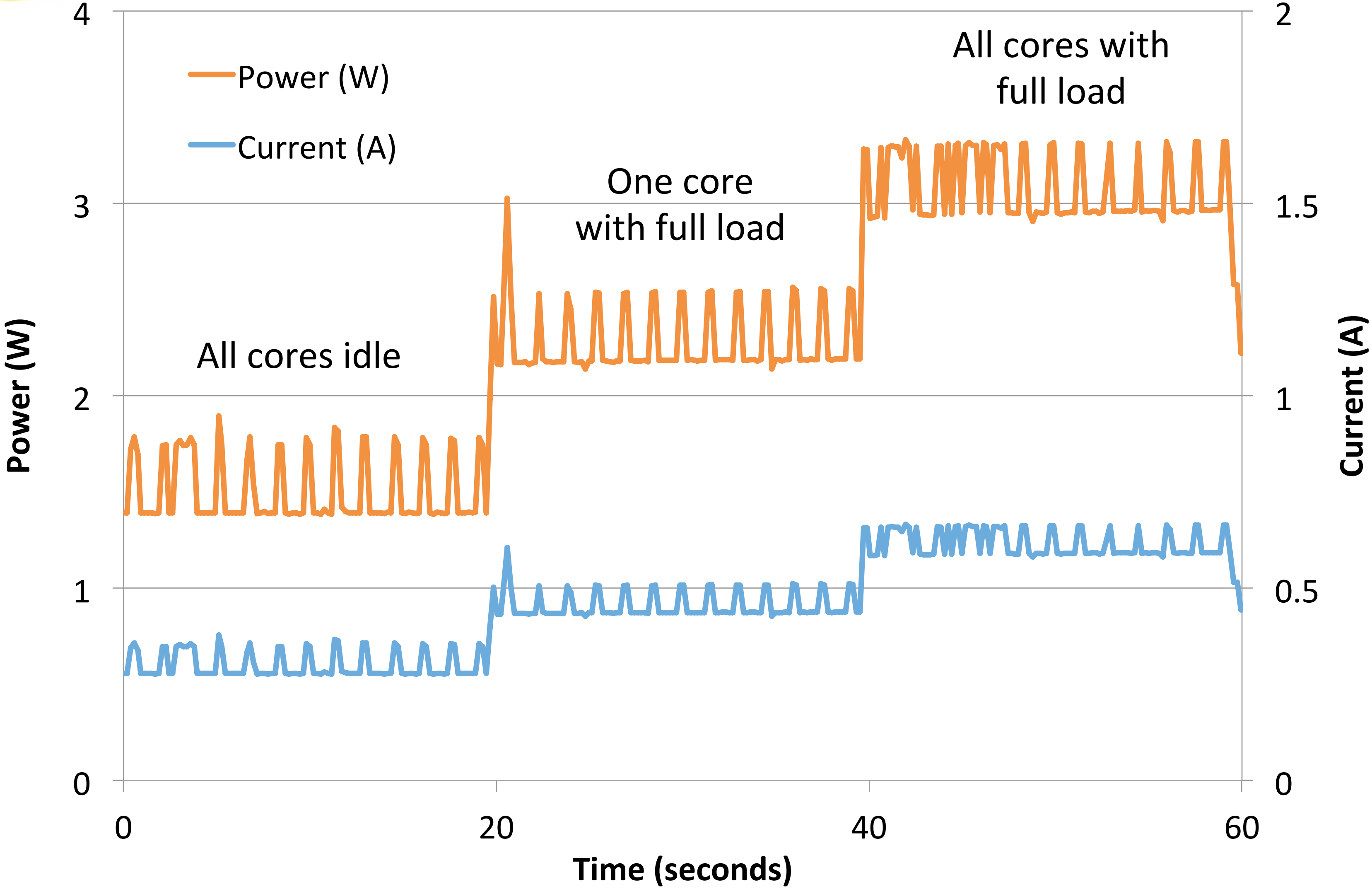
	Overall	Power Consumption	Computational Power	Comms	Development Cost (SW)	Development Cost (HW)	Modular
Priority		1	2	1	2	2	1
CM-T54	**3.95**	3	5	5	4	4	5
CM-FX6	**3.55**	3	4	5	2	4	5
BeagleBone Black	**2.69**	5	1	5	5	5	1
COMe-mBTi10	**3.85**	4	5	3	4	4	5
SMARC-xSBTi	**3.51**	2	5	5	4	4	5
Nitrogen6x-SOM Q	**3.89**	3	4	5	4	4	5
Nitrogen6x-SOM D	**3.75**	3	3	5	4	4	5
Nitrogen6x-SOM S	**4.06**	4	3	5	4	4	5
Wandboard Dual	**4.42**	4	4	5	5	5	5

LLP – ***Wandboard Dual***

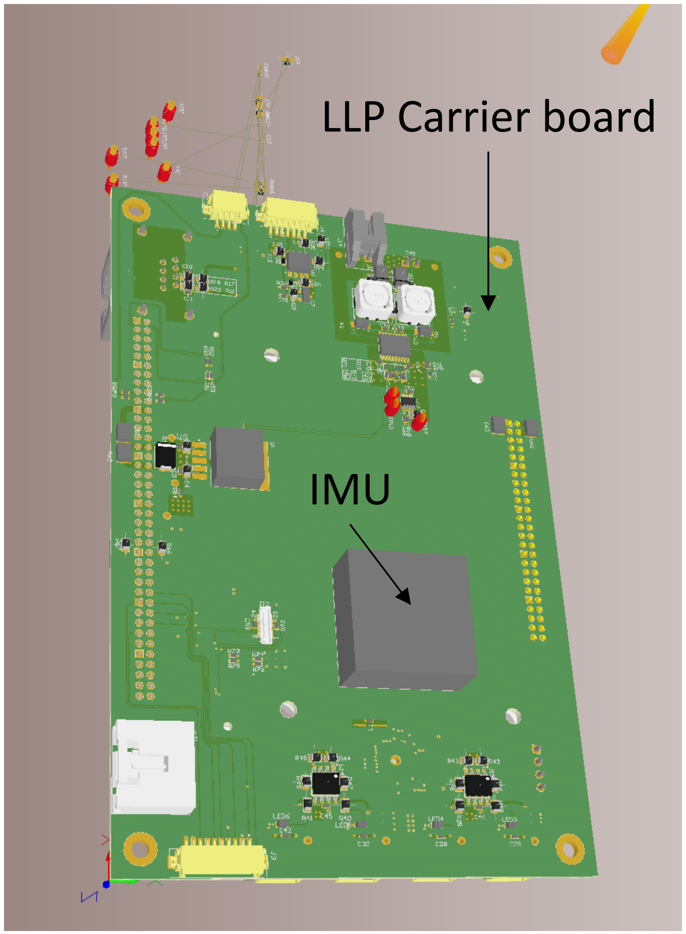


- i.MX6 Dual Cortex-A9
- 1 GB RAM
- Edge connector with carrier board
- 80mm x 60mm
- Ubuntu support

Power Consumption



LLP Carrier Board



Bottom

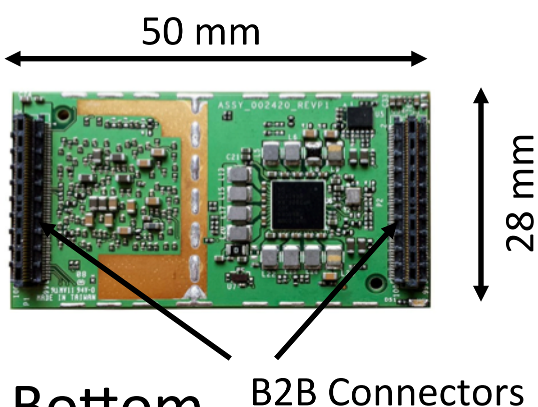
Top

MLP & HLP Trade Study

	Overall	Power Consumption	Computational Power	Comms	Software Development Cost	Hardware Development Cost	Modularity
Priority		2	1	1	2	3	1
Odroid-XU3	**2.74**	2	5	4	5	4	1
CM-FX6	**2.90**	3	2	3	4	2	4
VAR-SOM-OM54	**3.12**	3	3	5	1	3	5
phyCORE-OMAP5430	**3.12**	3	3	5	1	3	5
OMAP5430 Pico ITX	**2.61**	3	3	5	3	4	1
DragonBoard 8074	**3.04**	1	5	5	1	4	5
DragonBoard 8084	**3.04**	1	5	5	1	4	5
IFC6410	**2.31**	2	4	2	5	4	1
IFC6540	**2.59**	1	5	5	4	4	1
IFC6400	**3.03**	2	4	2	5	3	4
IFC6501	**3.14**	1	5	3	4	2	5
COMe-mBT10	**3.11**	1	5	3	3	4	4

MLP & HLP – ***IFC6501***

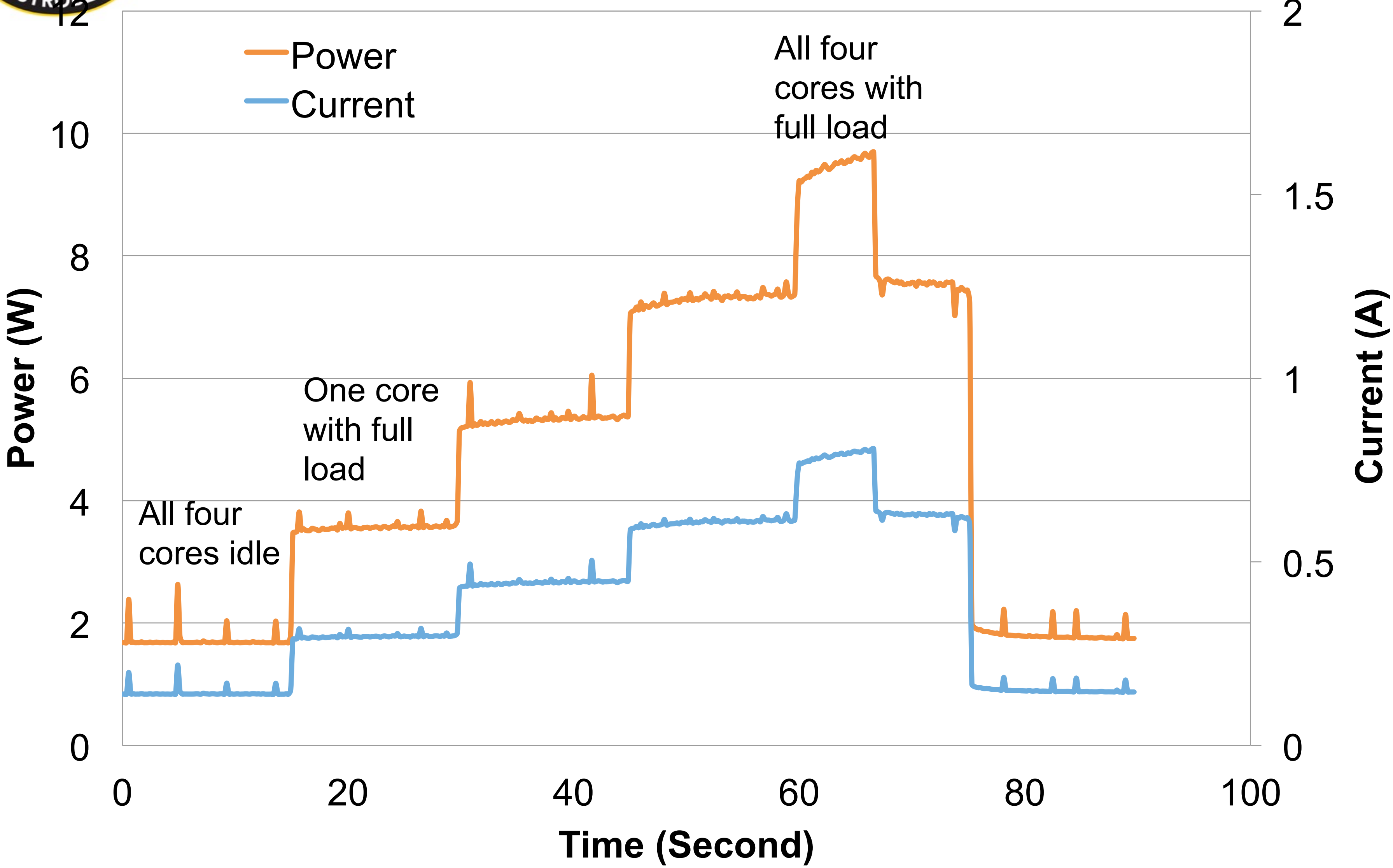
Top



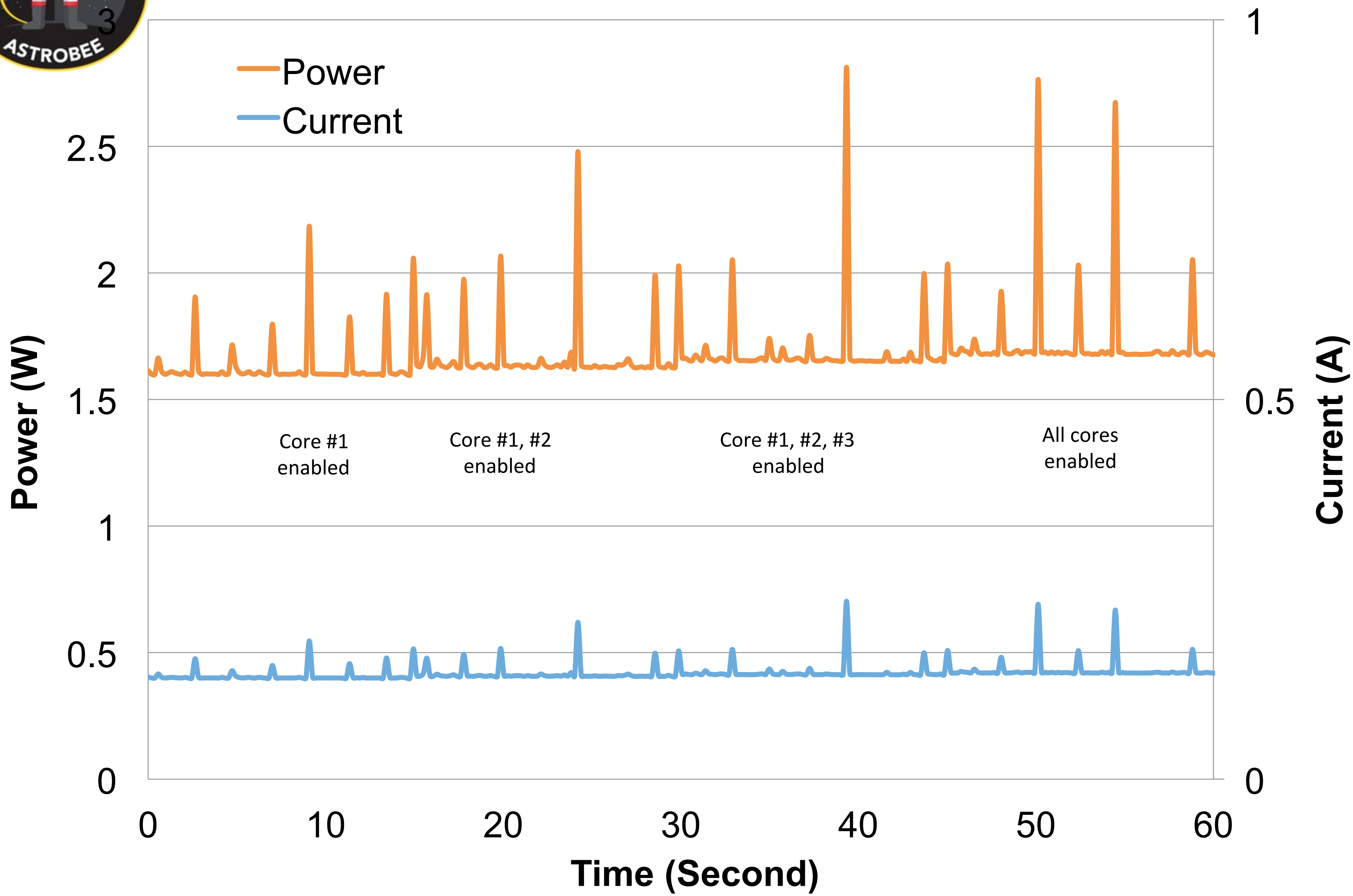
Bottom

- Inforce Computing's System-on-Module (SoM)
- Qualcomm SnapDragon 805
  - Cortex-A15 class (ARMv7 32-bit)
  - 2 GB RAM
- 28mm x 50mm, 8 g
- Ubuntu and Android support

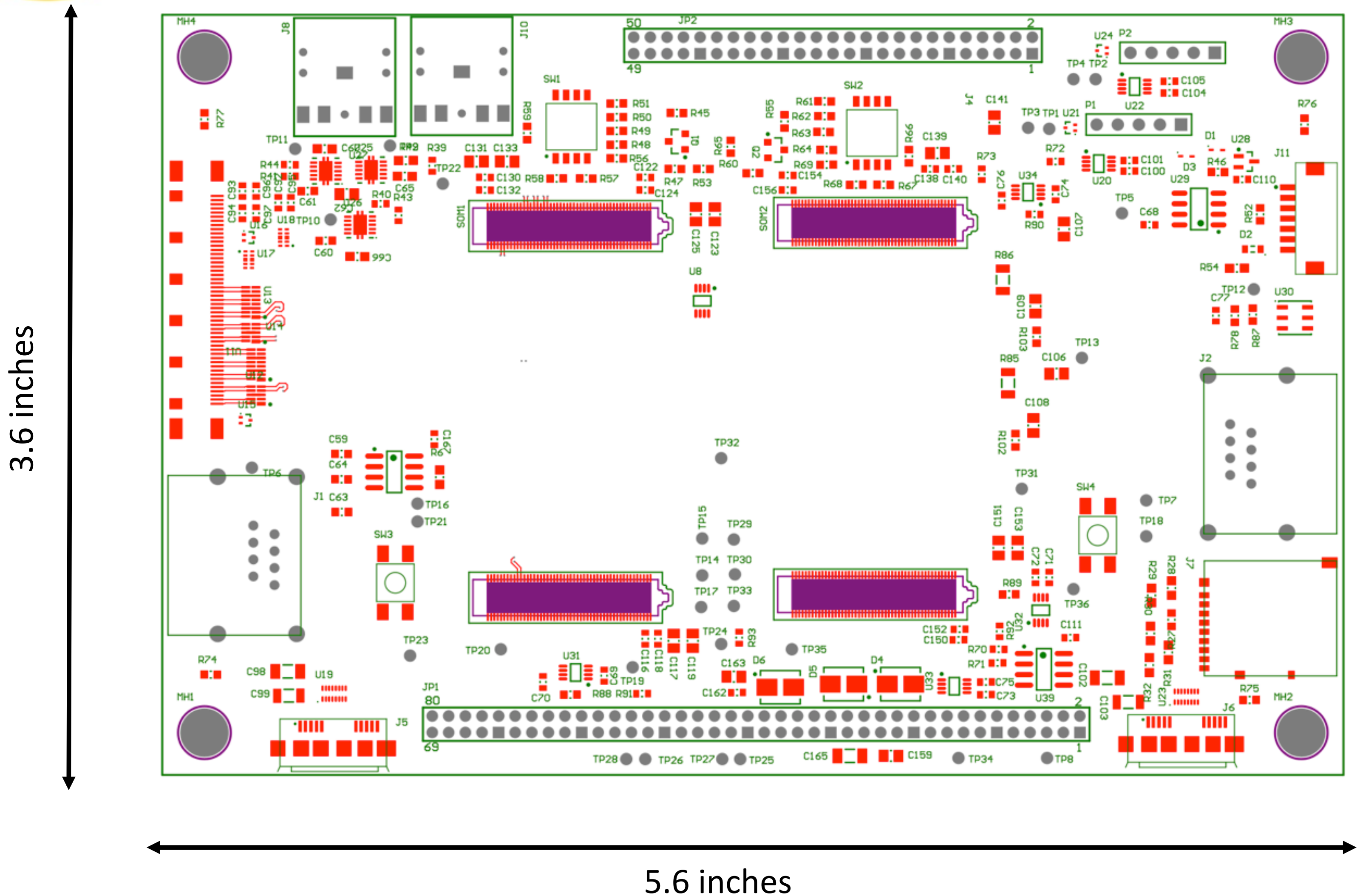
Active Power Consumption



Idle Power Consumption



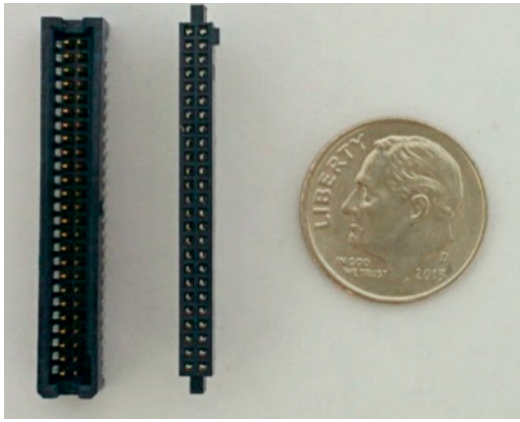
MLP+HLP Carrier Board



Touch Screen

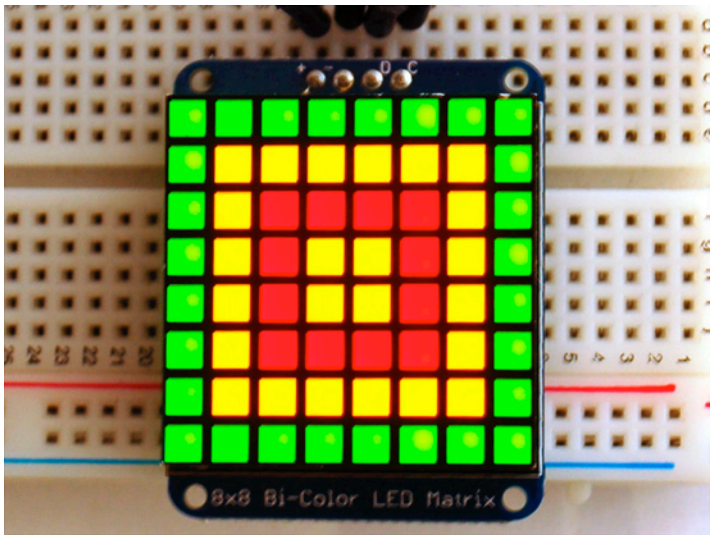
- 4” 800x480
- MIPI DSI
- Capacitive touch screen
- 60mm x 40mm x 1.8mm

Peripheral Bay Connector



- Samtec 0.05” TFM/SFM connector
- 50 pin connector
- V_{batt}, GND
- USB 2.0

LED Signal Indicator

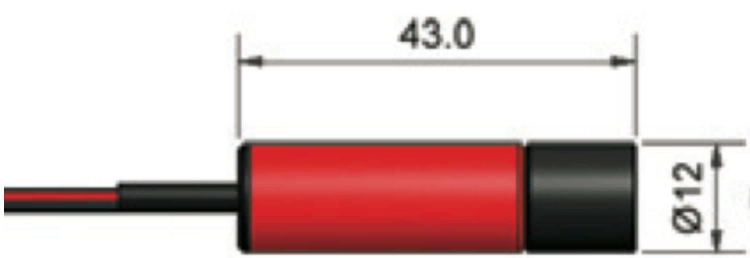


- 8x8 bi-color LED matrix
- I2C control
- 33mm x 41mm x 4mm
- Maximum power consumption: 120 mA @ 3.3V

ISS ROBOTIC FREE FLYER
ASTROBEE

Laser Pointer

- Direct Emission Green Laser
- 520 nm
- 0.9 mw



LED Flashlight

- 3.3 V @ 1 A
- 216 lm
- 45^{o} viewing angle
- 127^{o}C at full power

Astrobee EPS Subsystem

Design Overview

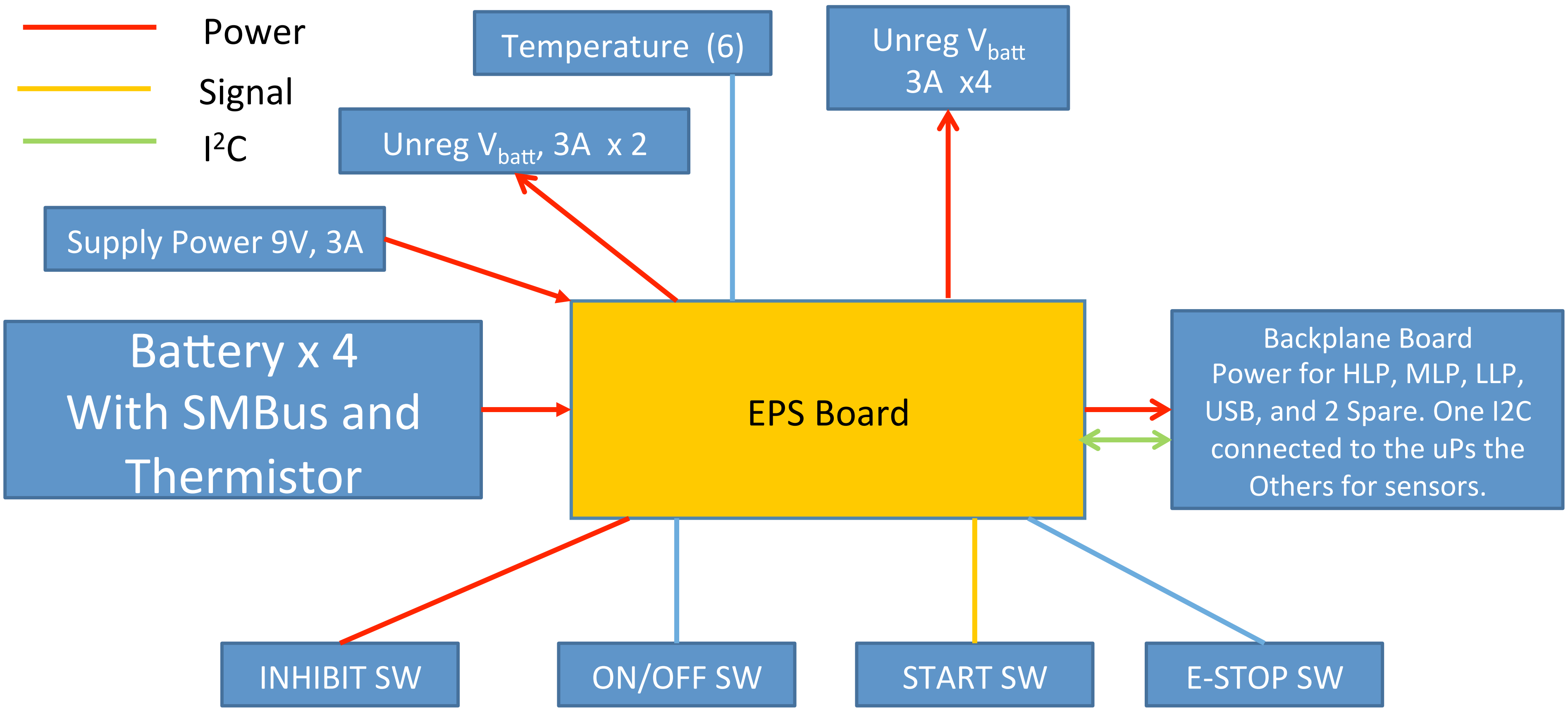
Subsystem Team

- Dmitriy Arbitman (ARC-RE)
- Steve Battazzo (ARC-RE)
- Jon Dewald (ARC-RE)
- Brandon Gigous (ARC-TI, Intern)
- Jason Lum (ARC-TI)
- Nghia Mai (ARC-RE)
- In Won Park (ARC-TI)
- Jongwoon Yoo (ARC-TI)
- Shang Wu (ARC-RE)
- Vinh To (ARC-TI)

Design Drivers

- Provide power to Astrobee
- Recharge through dock adapter
- Support up to 4 batteries
- Monitor system V & I

Architecture Diagram



Functions

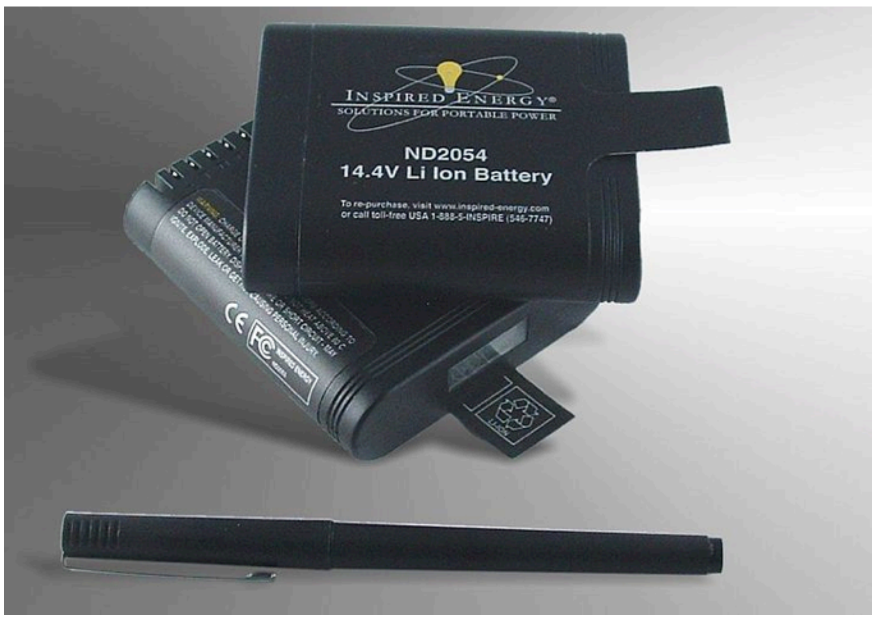
- Provide power to:
  - LLP, MLP, & HLP
  - Prop modules
  - Payloads
- Monitor:
  - Voltage
  - Current
  - Temperature
- Protection
  - E-stop
  - Thermal
  - Power

Power

- Input Power:
  - 9 V to 28 V input (Default at 9V) @ 3A.
- Output Power
  - 2 power lines with Unreg V_{batt} @ 3A MAX.
  - 4 power lines with Unreg V_{batt} @ 3A MAX.
- Storage Power: Can connect up to 4 batteries (Power = 196 Wh)
- EPS Board Power Consumption: <0.4W idle

Battery

- Battery pack should be < 80 Wh
- Inspired Energy Battery 14.4V option
- Older version of battery on Station



Cell Array	4S1P
Voltage	V_{max}=16.8V, V_{nom}=14.4V, V_{cutoff}=9.6V
Max Discharge Current	4A
Max Continuous Power	40W
Weight	234 g
Comm	SMBus
Dimension	23mm x 87mm x 79mm

Monitor

- Battery Voltage
- Input V & I
- System V & I
- Temperature
  - 2 on board & 6 external
  - Battery
- Battery State (SMBus)

Protection

- Low Battery Voltage Protection: Turn system OFF when Batteries get down to 6.2V and Will not turn on until Battery voltage back up to 6.9V
- Hardware Current limit, EPS 3.3V and EPS 5V
- Software Current limit: All System and Sub-systems current can set to the safe current level through software
- On Board E-STOP
- Thermal protection for the Batteries, Motors, and Boards set in software to turn OFF

Others Function

- One wire EEPROM: Used for board ID. Might add in Board burn-in time tracking on the next rev. if space available
- 6 LEDS arrays for error or debug purpose.
- 45 LEDS and 54 Test points: Use for Power and communication indicators to support hardware test and soft debug.

Component List

- EPS board
- Connector board
- Batteries

Astrobee External Sensors

Design Overview

Subsystem Team

- Dmitriy Arbitman (ARC-RE)
- Steve Battazzo (ARC-RE)
- Jon Dewald (ARC-RE)
- Brandon Gigous (ARC-TI, Intern)
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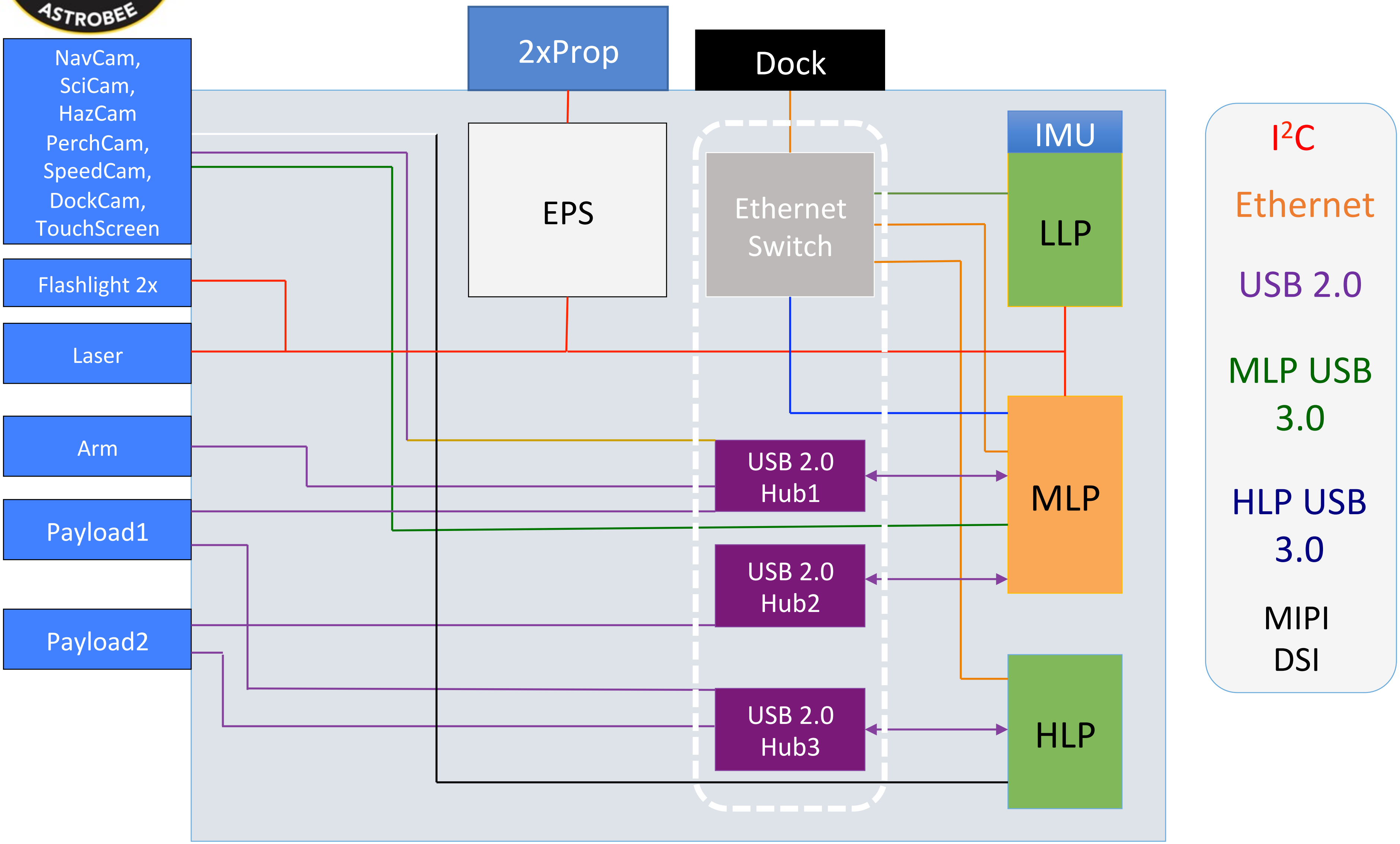
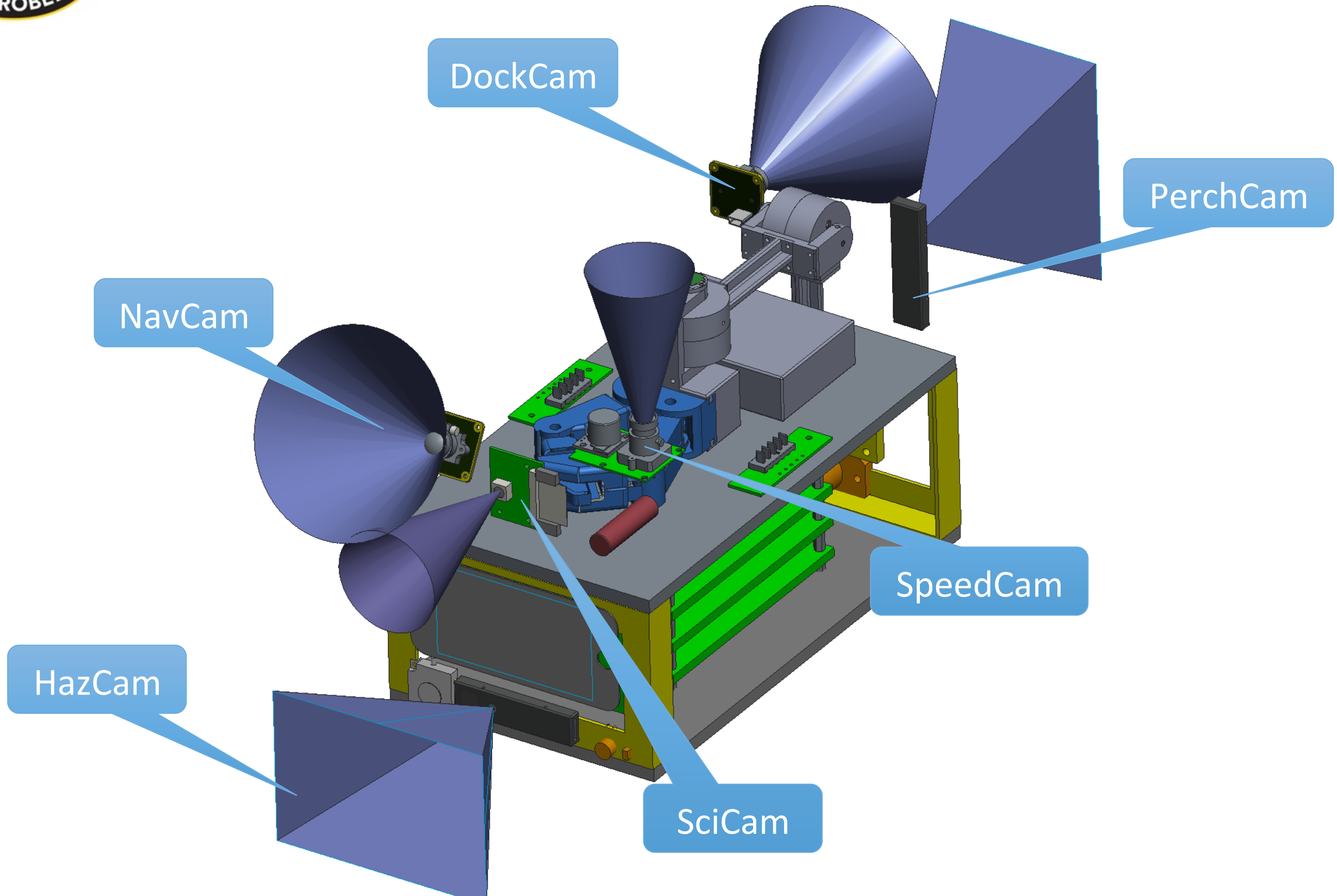
Architecture Diagram



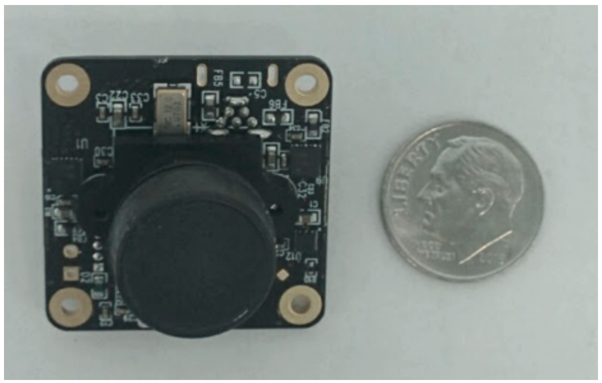
Component List

Sensor	Purpose	Direction
NavCam	Localization – Optical flow, Sparse Mapping	Forward
DockCam	Localization – AR tag extraction	Aft
SciCam	HD video streaming and recording	Forward
SpeedCam	Localization – Optical flow	Up
HazCam	Obstacle avoidance	Forward
PerchCam	Handrail detection	Aft

Sensor Layout



NavCam & DockCam

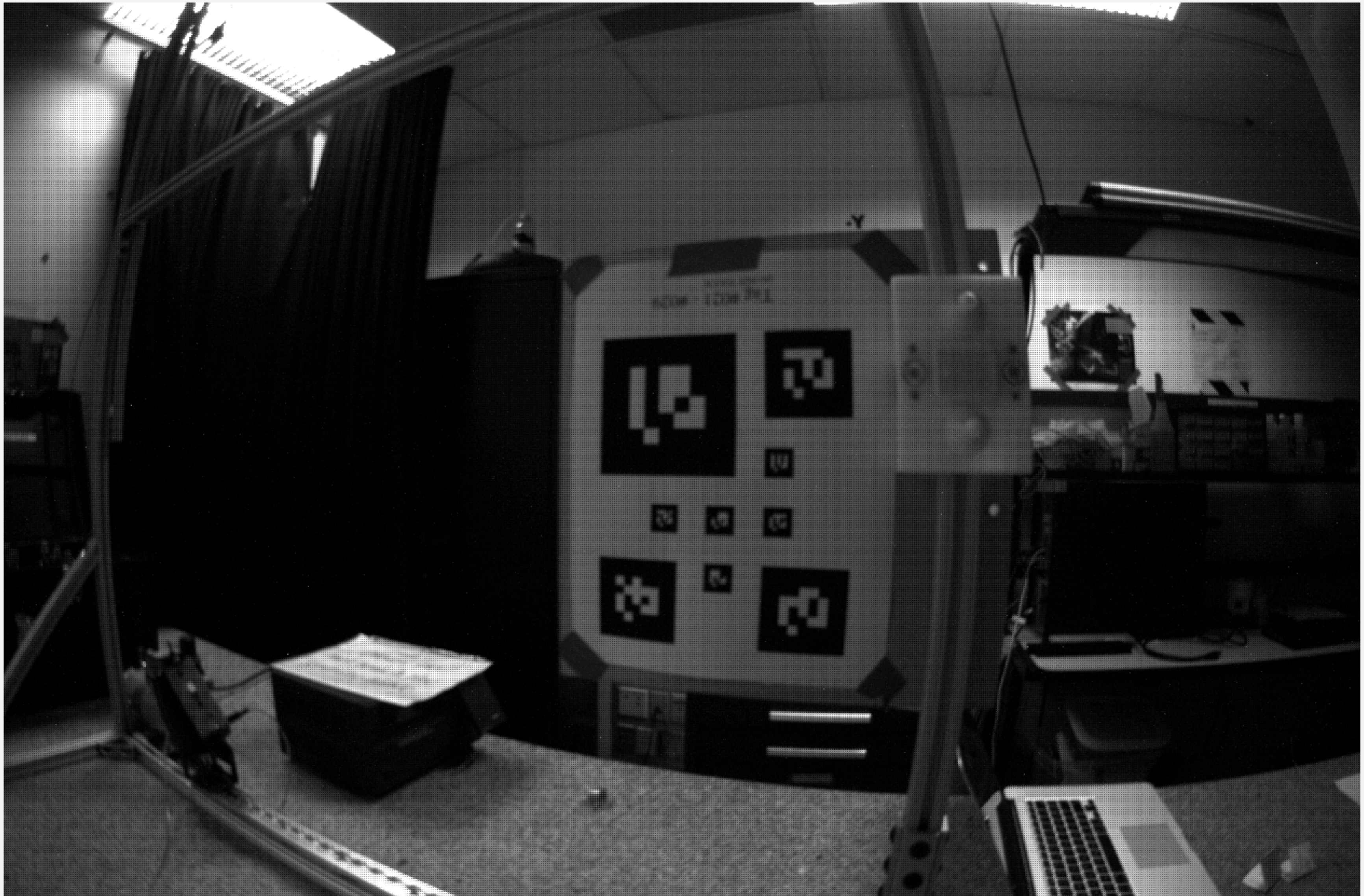


DFM 42BUC03-ML

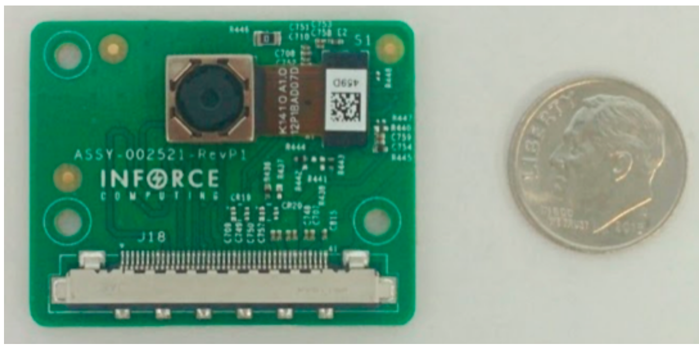
Fisheye lens

- The Imaging Source DFM 42BUC03-ML
- USB 2.0
- 1280x960 pixels @ 25 FPS
- Fisheye lens: FOV D 130
- 30 mm x 30 mm x 15 mm, 7 g
- 1.25 watts

NavCam & DockCam

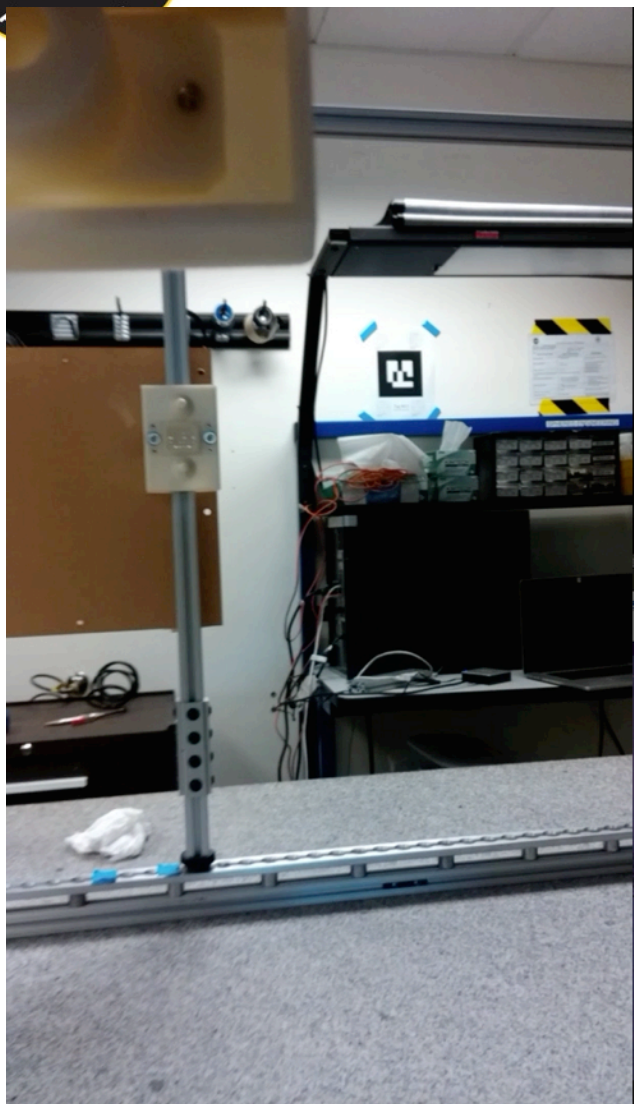


SciCam



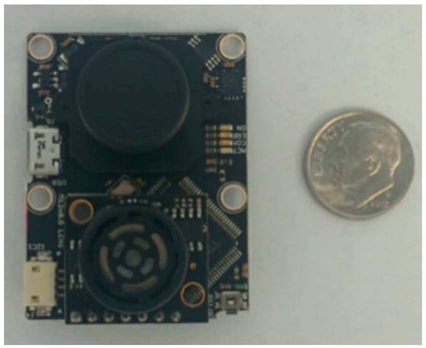
- Sony IMX135
- 13 Mega Pixel
- MIPI-CSI
- Auto focus support
- FOV: 54.8^0 H x 42.5^0 V
- 38.1 x 30.5 x 1.5 mm, 5 g

SciCam



- Resolutions & Frame Rates
  - Full resolution @ 24 FPS
  - Half resolution @ 48 FPS
  - 1080p @ 30 FPS
  - 1080p @ 60 FPS
- CPU & Disk Usage for Recording
  - 1080p @ 30 FPS → 40 % of a core, 150 MB/min
  - 720p @ 30 FPS → 35 % of a core, 100 MB/min
  - 480p @ 30 FPS → 30 % of a core, 17 MB/min

SpeedCam



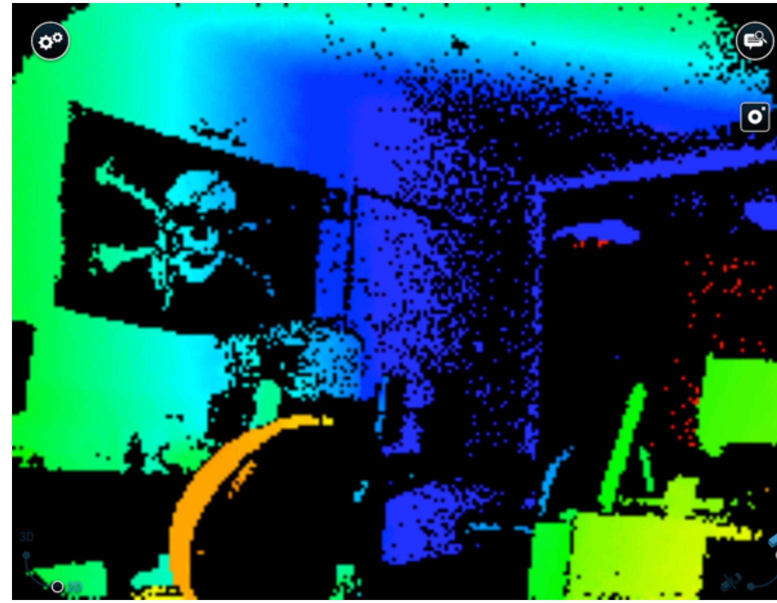
- PX4Flow
- Optical flow processing on 4x4 binned image at 400 Hz
- On board gyro and sonar
- USB, I2C support
- 0.6 W

HazCam & PerchCam

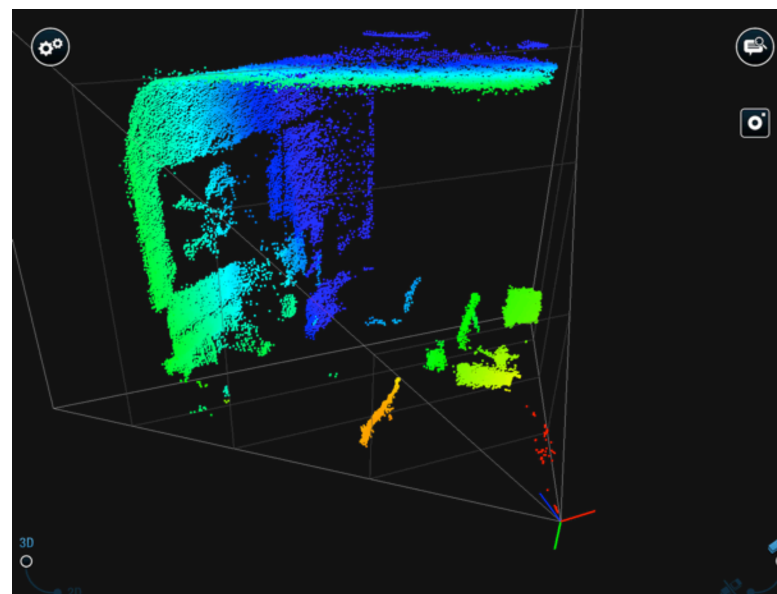
- CamBoard pico flexx
- 0.1 – 4 m range
- USB 2.0, 300 mW average
- 68mm x 17mm x 7.25mm
- 62^{o} x 45^{o}, 224 x 172 pixels

HazCam & PerchCam

2D Projection



3D Depth

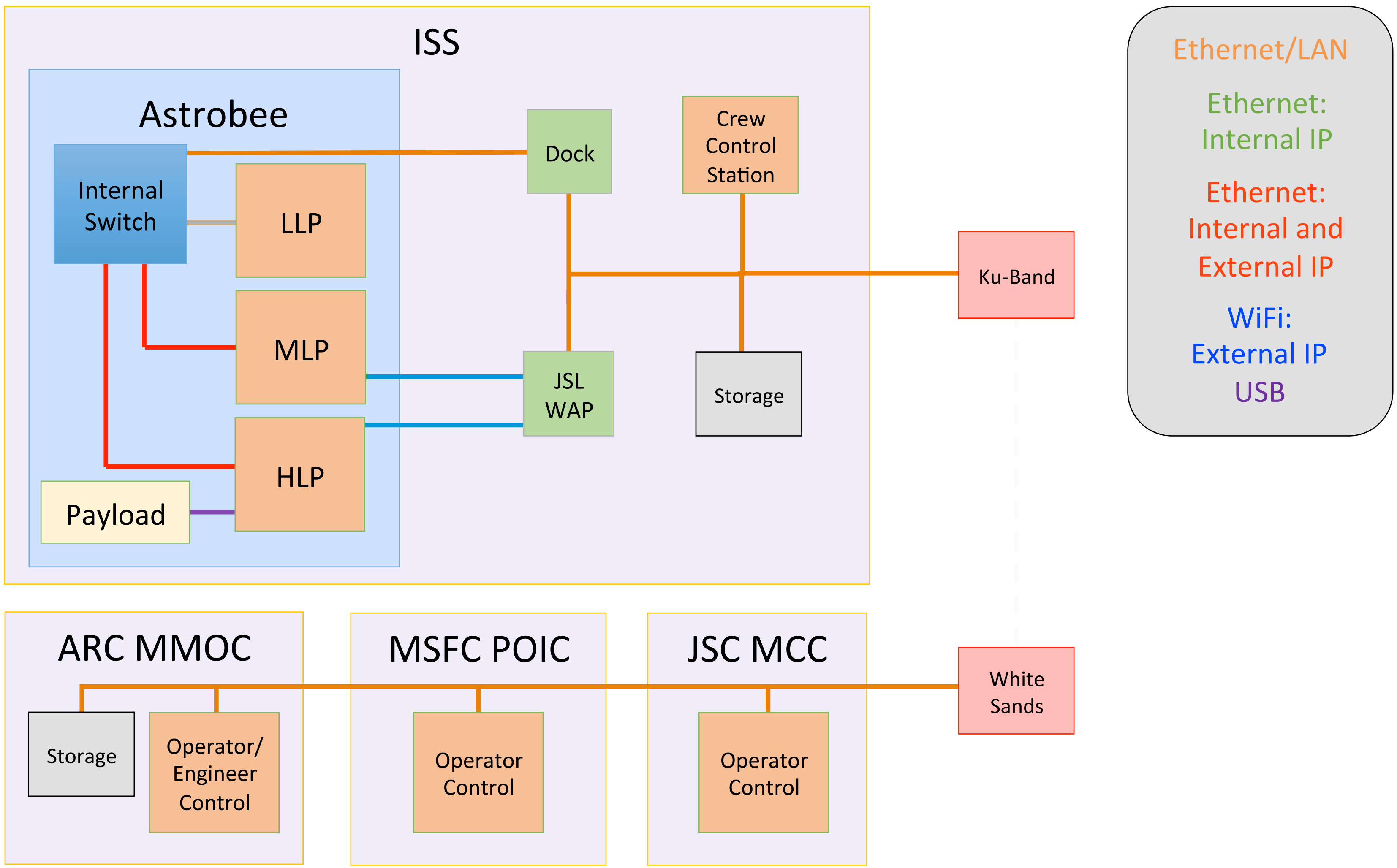


Comms

Team

- Ted Morse
- Vinh To
- Jason Lum (alum)

Comms Block Diagram

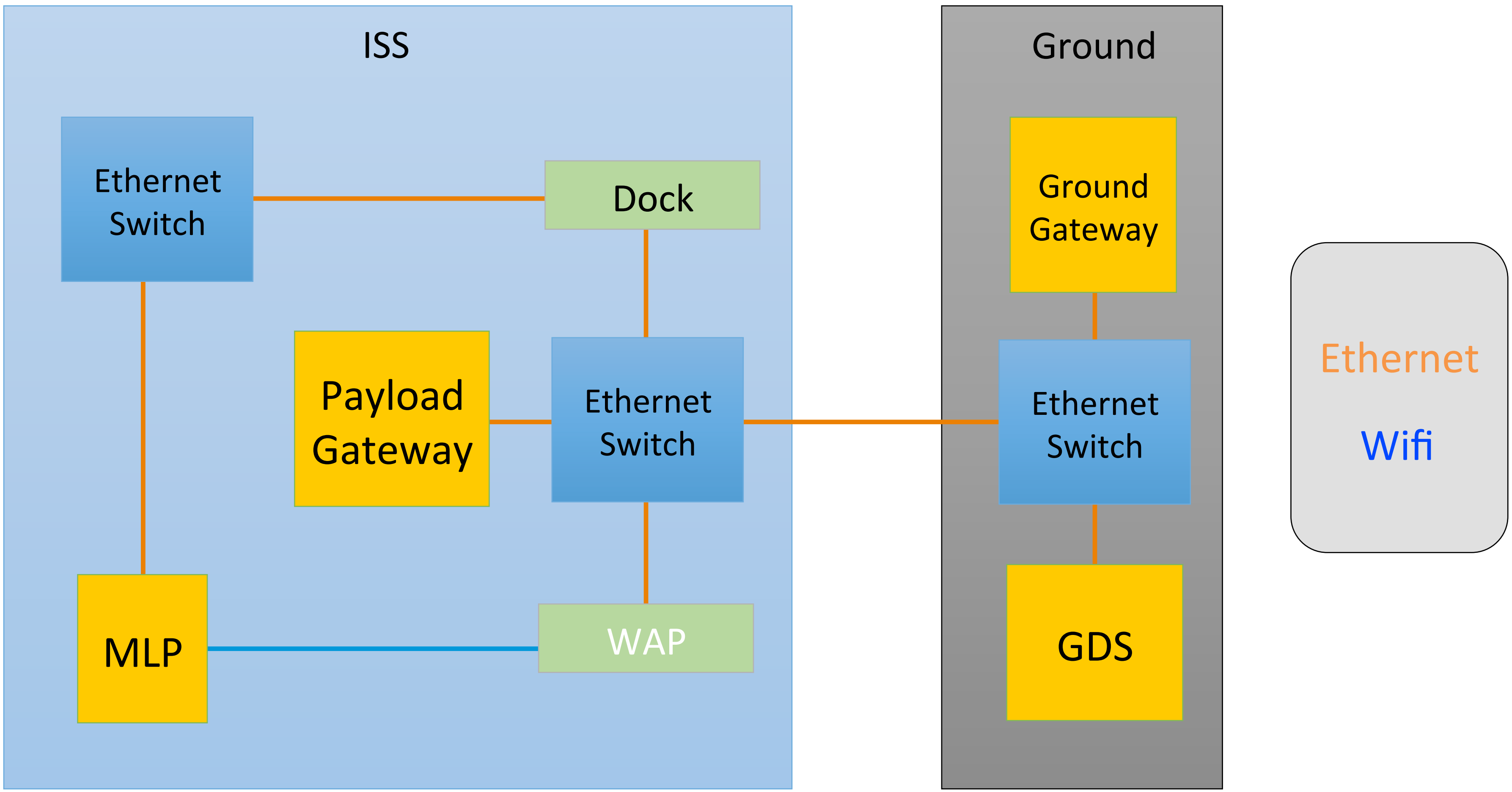


Comms Setup

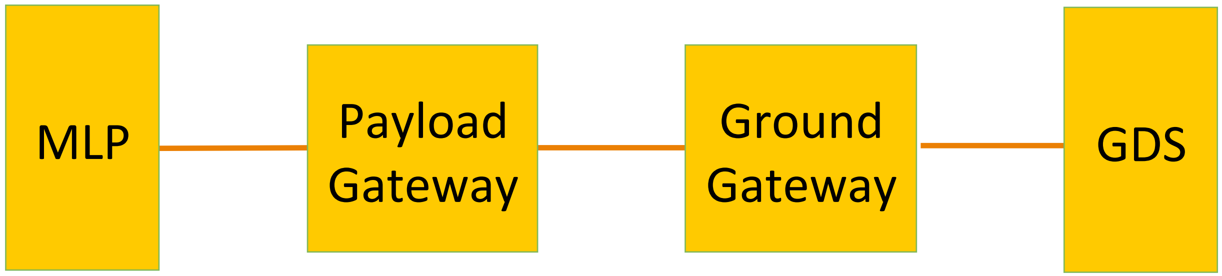
- MLP Wifi is used for comms to GDS, including video. (and possibly Astrobee-to-Astrobee.)*
- Internal IPs are used for FSW messaging.*
- External wired IPs are generally used for large file transfers, upgrades, etc.
- HLP not actively used, but enabled.

*Actual protocols defined by FSW & FSW/GDS ICD – but we all know it's DDS & ROS.

TReK CFDP DTN Diagram



TReK CFDP DTN Setup



- TReK CFDP DTN is a reliable file transfer protocol.
- Data is sent serially through each node.
- The KU Forward connection is between the gateways.
- Data is stored at the gateways during a LOS.

Antenna

- 2.4 GHz/5.8 GHz Wifi antenna
- ~3dBi/5dBi gain
- Adhesive tape mounting
- Paper thin

Astrobee FSW Subsystem

Design Overview

FSW Subsystem Team

- Staff
  - Brian Coltin
  - Lorenzo Flückiger (lead)
  - Ted Morse
- Postdoc
  - Dong-Hyun Lee
- Intern
  - Mike Watterson
- Alumni
  - Oleg Alexandrov
  - Ravi Gogna
  - Zack Moratto

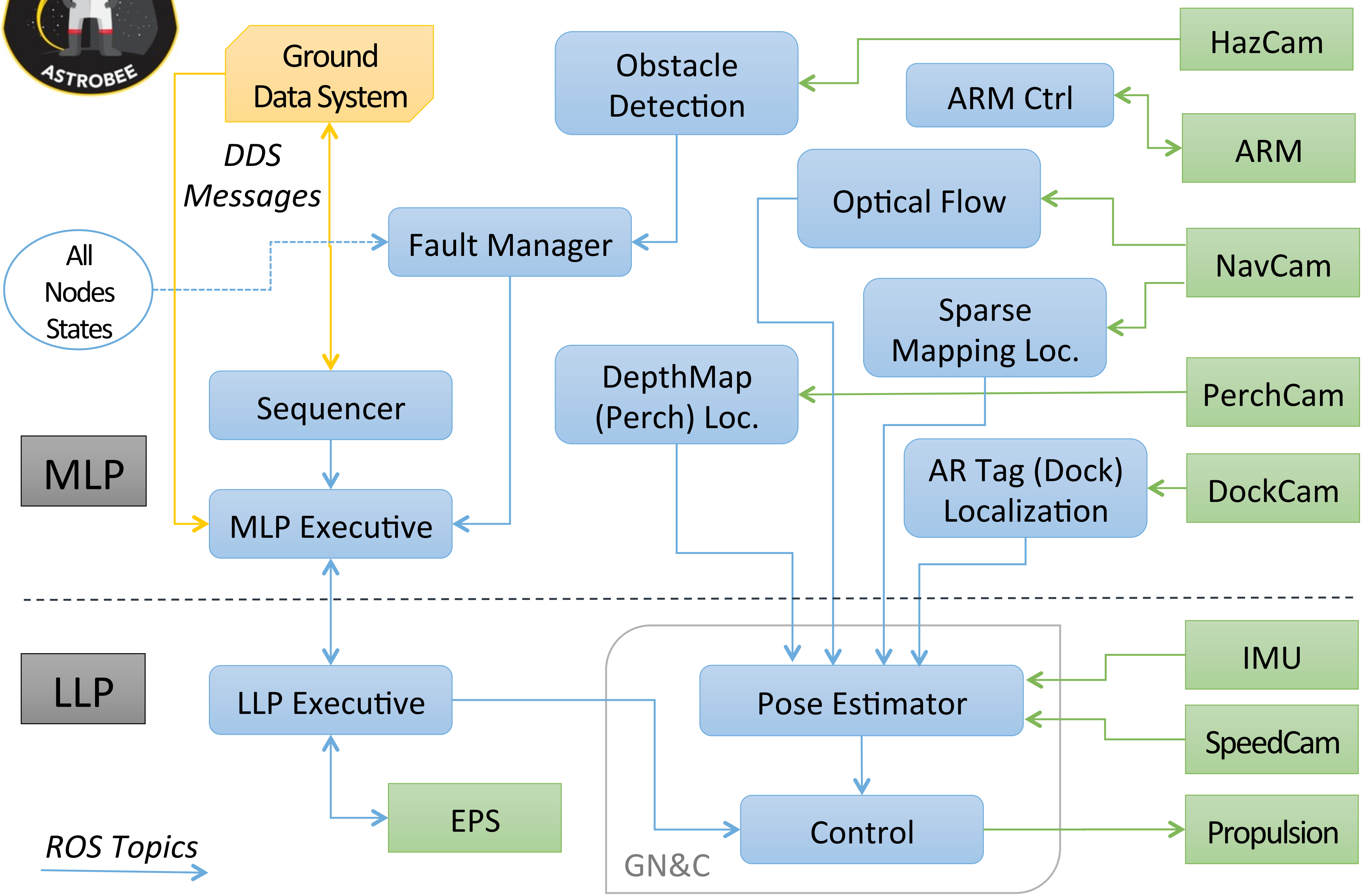
Astrobee FSW Features

- Manage Astrobee sensing and actuation
- Navigate and localize within the ISS
- Perform autonomous docking (+ return to dock)
- Perform autonomous perching
- Manage multisensory interaction with the crew
- Support "Guest Science" operations
- Support plan based automated tasks
- Support remote control from ground

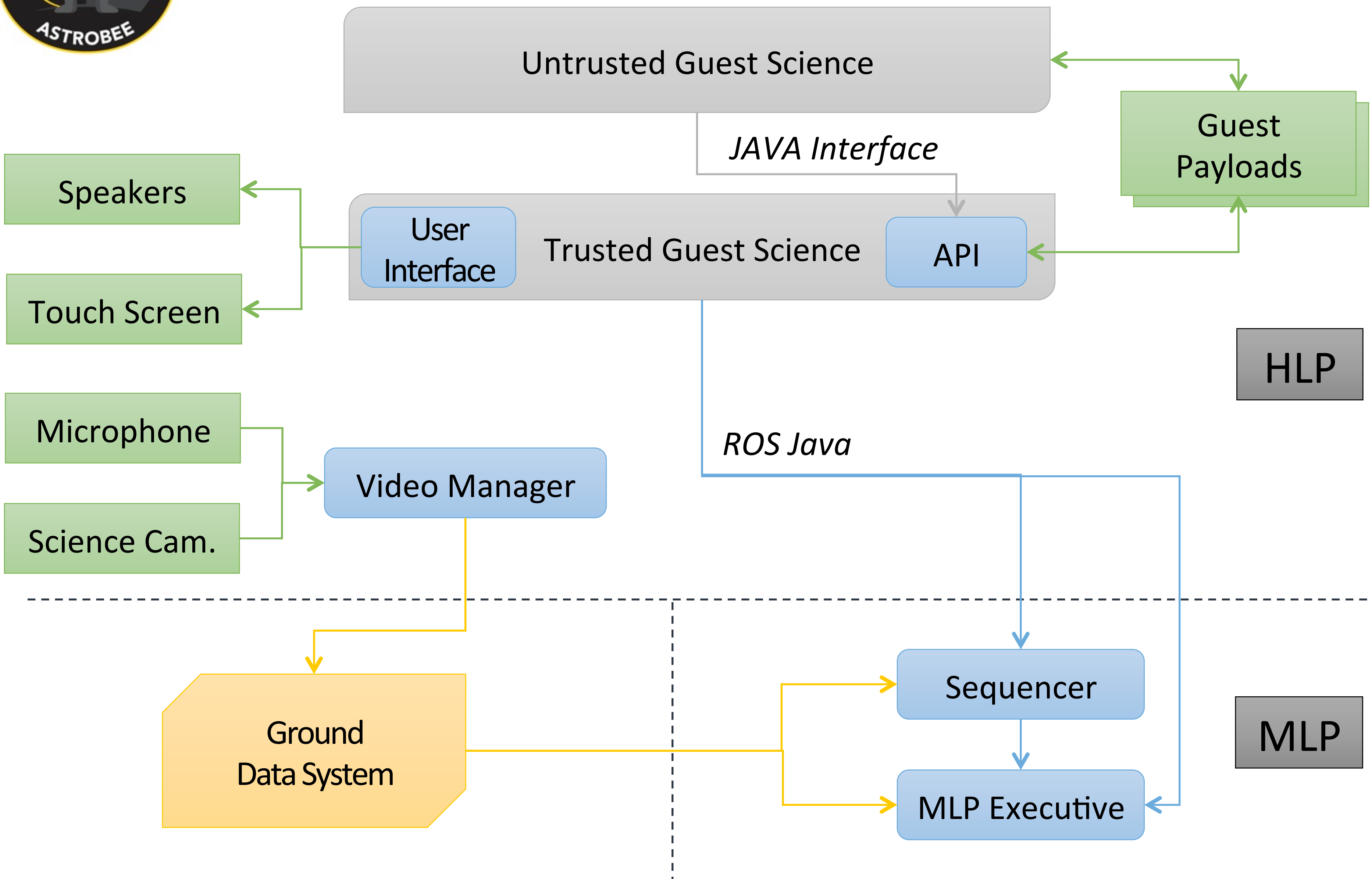
Selected HW Architecture

- *Three processors to isolate guest code and 100 Hz control loop*
- **Low Level Processor** (LLP)
  - Runs 100 Hz EKF and propulsion control loop
- **Mid Level Processor** (MLP)
  - Runs absolute localization algorithms, obstacle detection, sequencer, communications
  - Heavy processing power used by vision
- **High Level Processor** (HLP)
  - Interface with Science Camera and Display
  - Encodes video with dedicated hardware
  - Runs guest science code

System Architecture (MLP+LLP)



System Architecture (HLP)



FSW Components

- OS (Communication Framework)
- *Pose Estimation + Propulsion Control*
- Fault Management
- Executive (Mode Manager)
- Sequencer (Plan Execution)
- Online localization (inputs for absolute pose)
  - Navigation
  - Docking
  - Perching
- Offline mapping for localization

Communication Framework

Candidates
Common Flight Executive (CFE)
Robotic Operating System (ROS)
Mobile Robot Programing Toolkit (MRPT)
Joint Architecture for Unmanned Systems (JAUS)
IRG RoverSW (SORA + **RAPID**)
Data Distribution Service (DDS)

Selected solution is hybrid of:
- ROS for onboard messaging
- DDS for remote comm.

- Key Factors for ROS Selection (vs. CFE):
  - Distributed/Localized Unified Messaging
  - Better Service Isolation
  - Library of Robotics Algorithms Available
- Key Factors for DDS + RAPID
  - Multiple Configurable Quality Of Service (QoS)
  - ISS Tested + Heritage from SmartSpheres

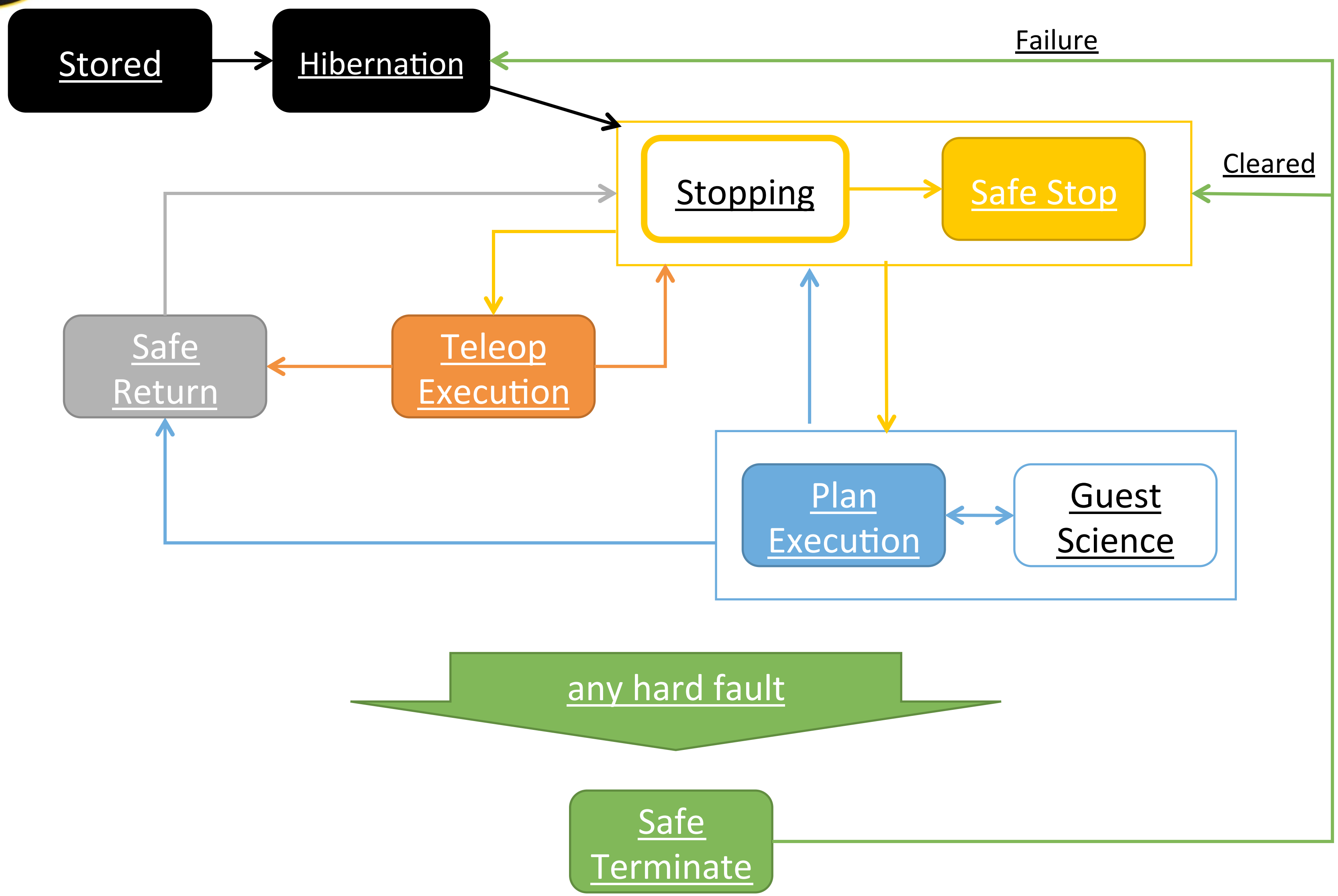
Fault Management

- Faults can enabled, triggered, or inhibited.
- All faults are sent to a central fault management module.
  - Fault management module looks up fault status and the response in a table which can be easily modified
  - Typical response is a state change, often to safe stop or safe terminate
- Specific examples:
  - **Heart beats**: A heart beat manager listens to heart beat topics, triggers a fault if process stops responding
  - **Obstacle Detection**: An obstacle detection module triggers a fault that moves to safe stop if an obstacle is in the way

Executive Nodes

- Executive Nodes are responsible for keeping track of all states.
- There are Executives on both MLP and LLP so that the operating mode is preserved in the event of a processor shutdown.
- Trajectory commands flow through Executives so that in case of an emergency, an Executive can execute a safe stop.
- Executives maintain operating mode through a finite state machine.

Operating Modes



Localization Design Drivers

Category	Localization Options	Assessment
Infrastructure + External Maps	ISS Wifi	Does not provide desired accuracy
	Beacons (passive/active)	Modifications to ISS / change dependent
Robot Builds Maps	Stereo Vision	"Metric" (shape) maps makes matching difficult
	3D sensors (LIDAR, ...)	
	Monocular Vision	"Features" maps efficient to filter

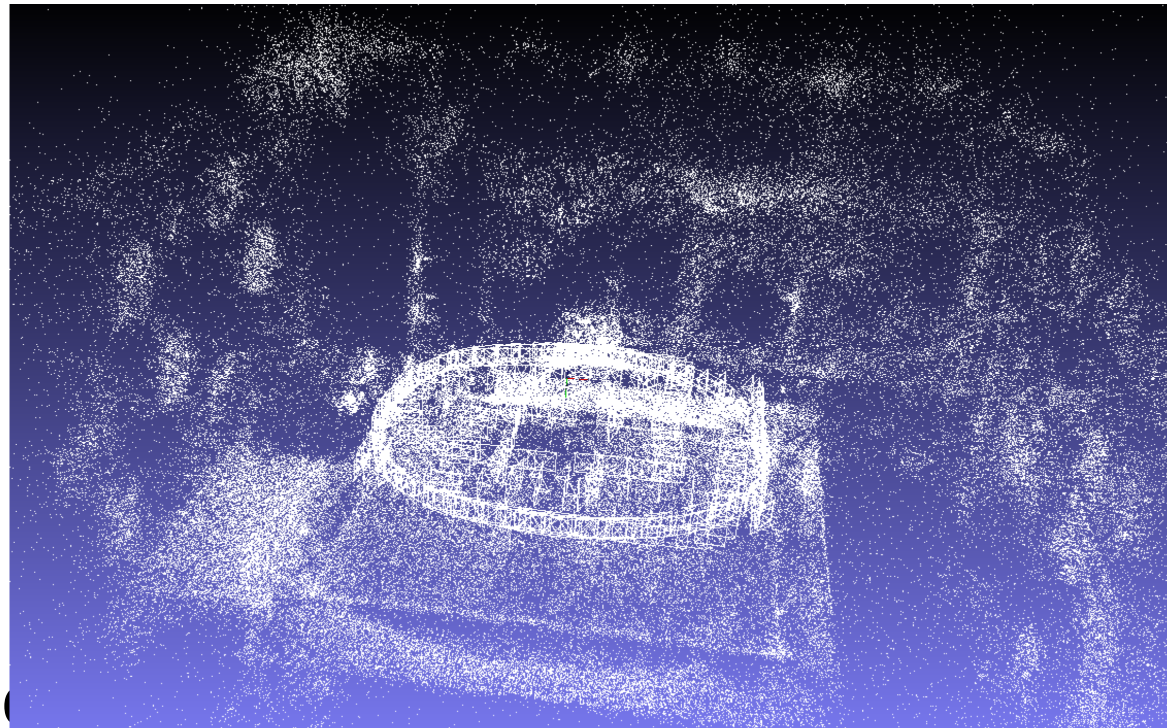
Requirements
Localize anywhere on ISS US segment
Minimize modifications to ISS
Cope with changing environment

Selected Solution (hybrid):
- Build and update maps offline
- Match visual features (3 modes) online for localization

Vision Node

- Four nodes send visual observations to EKF:
  - Sparse Mapping
  - AR Tag
  - Handrail Detector
  - Optical Flow
- AR tags used only when docking, handrail detector only when perching, sparse mapping otherwise
- Optical flow always runs
- All algorithms using the NavCam exist in the same Nodelet Manager so that images are passed by pointer

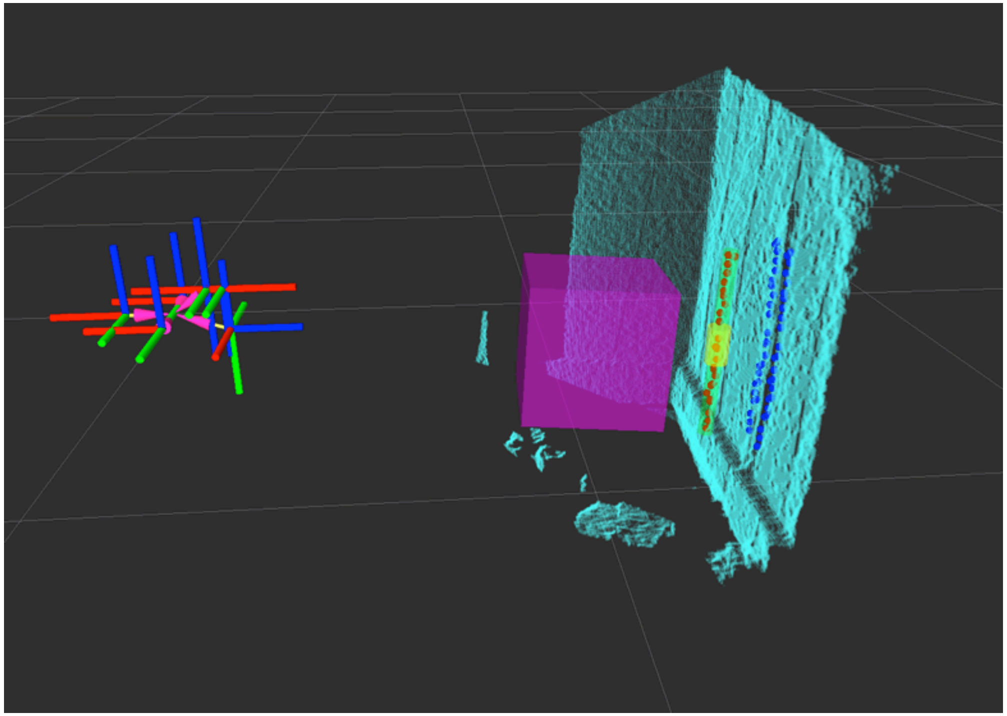
Sparse Mapping

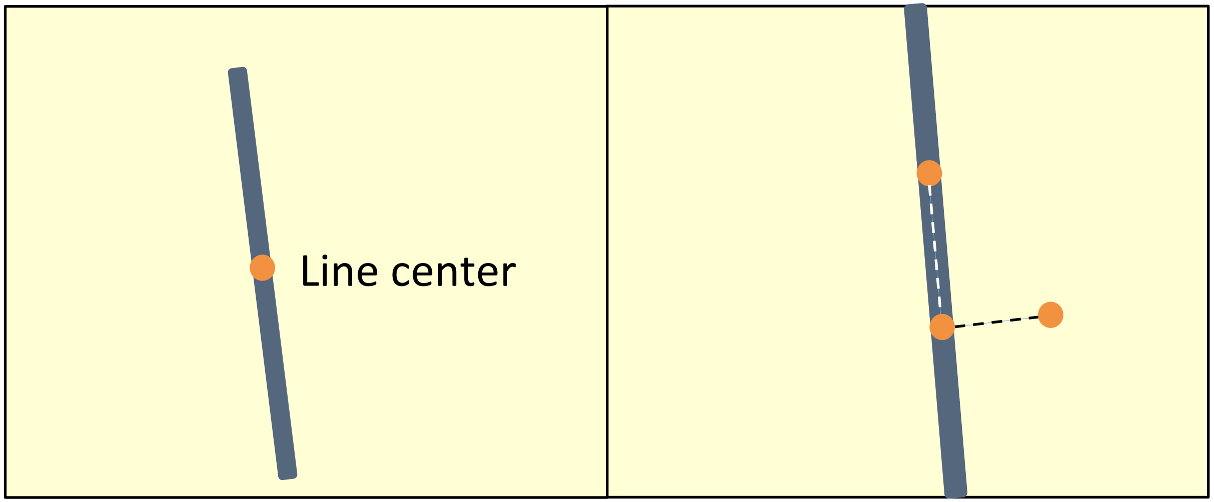


- Build maps from ISS imagery on ground
- EKF localizes with detected map points
- Map BRISK featur reference map to determine robot pose
- AR tags send same information to EKF from AR tags

Handrail Detection

- Uses PerchCam depth sensor
- Fit plane to wall behind handrail, line to handrail
- When perching, send points from handrail to EKF
- Uncertainty in direction along handrail when close





Guest Science

- Guest science runs as an Android app on the high level processor.
- Android permissions provide protection for the rest of the system.
- Two guest science modes based on level of trust and review
  - “Untrusted” Guest Science has access to limited high level API (Astrobee control performance not affected)
  - “Trusted” Guest Science is granted access to the full control stack, but requires it own review

Backups

DDS Bridge and Sequencer

- DDS contains our wireless connection to GDS.
- DDS publishes a compressed version of the plan to the sequencer.
- Both DDS and Sequencer publish commands. Executives keeping track of operating state determine if they get executed.

Trade Studies

OS Selection Criteria
Modularity
Service Isolation
Messaging Performance
Usability / Familiarity
Works on Target and Host
Record/Playback raw data
Maturity
Open Source

Localization Selection Criteria
Measurement Rate
Robust Against Drift
Robust Against Occlusion
Robust Against Env. Change
Algorithm Simplicity
Implementation Available
Localization Initialization
Target Platform

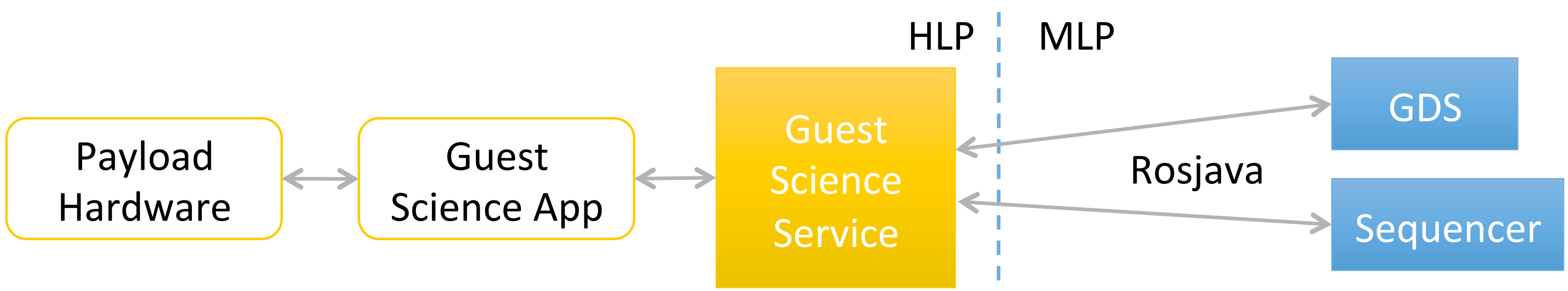
Operating Modes

- **Teleop Execution**: Obeying GDS commands.
- **Plan Execution**: Following a plan in the sequencer.
- **Guest Science**: Part of a plan, control handed to guest science code on HLP
- **Stopping:** Has a velocity, coming to a halt.
- **Stopped**: Maintaining current position.
- **Safe Terminate**: Turn off motors.
- **Hibernation**: Turn off motors and most modules.

AR tags docking

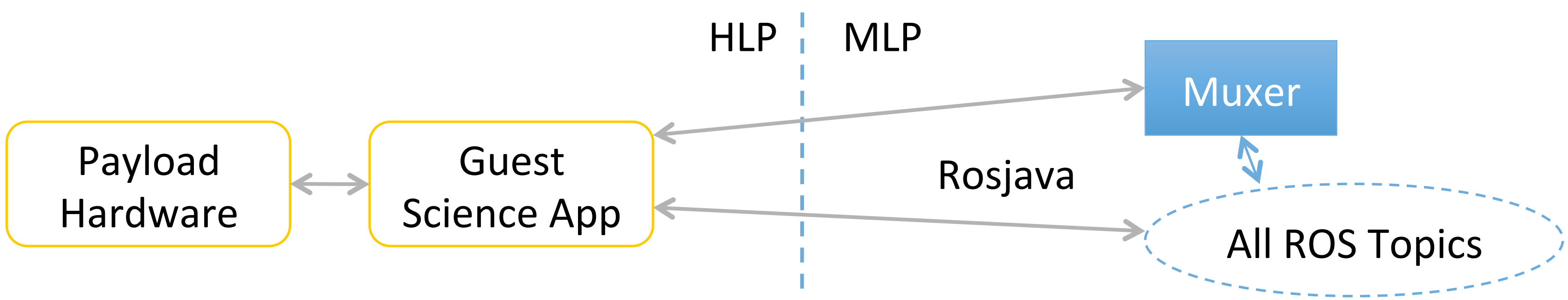
Untrusted Guest Science

- Limited functionality, Android permissions prevent general network access.
- Example: An RFID or microphone payload could survey the ISS.
- Apps are allowed to:
  - Execute plans, read robot status
  - Send messages to and from GDS
  - Communicate with payload devices
- Robustness is not compromised.



Trusted Guest Science

- Trusted apps have full network access, and can run rosjava to access all mid level processor topics and services.
- Example: An experiment to move a sloshing container of liquid could replace the EKF's outputs to control.
- A redirection node allows guest science to replace the inputs to certain nodes.
- Only limited robustness can be maintained, additional review of trusted apps needed.



Astrobee GN&C Subsystem

Design Overview

GN&C
Team Members

- Michael McIntyre (ARC-RE)
- Jesse Fusco (ARC-RE)
- Robert Nakamura (ARC-RE)

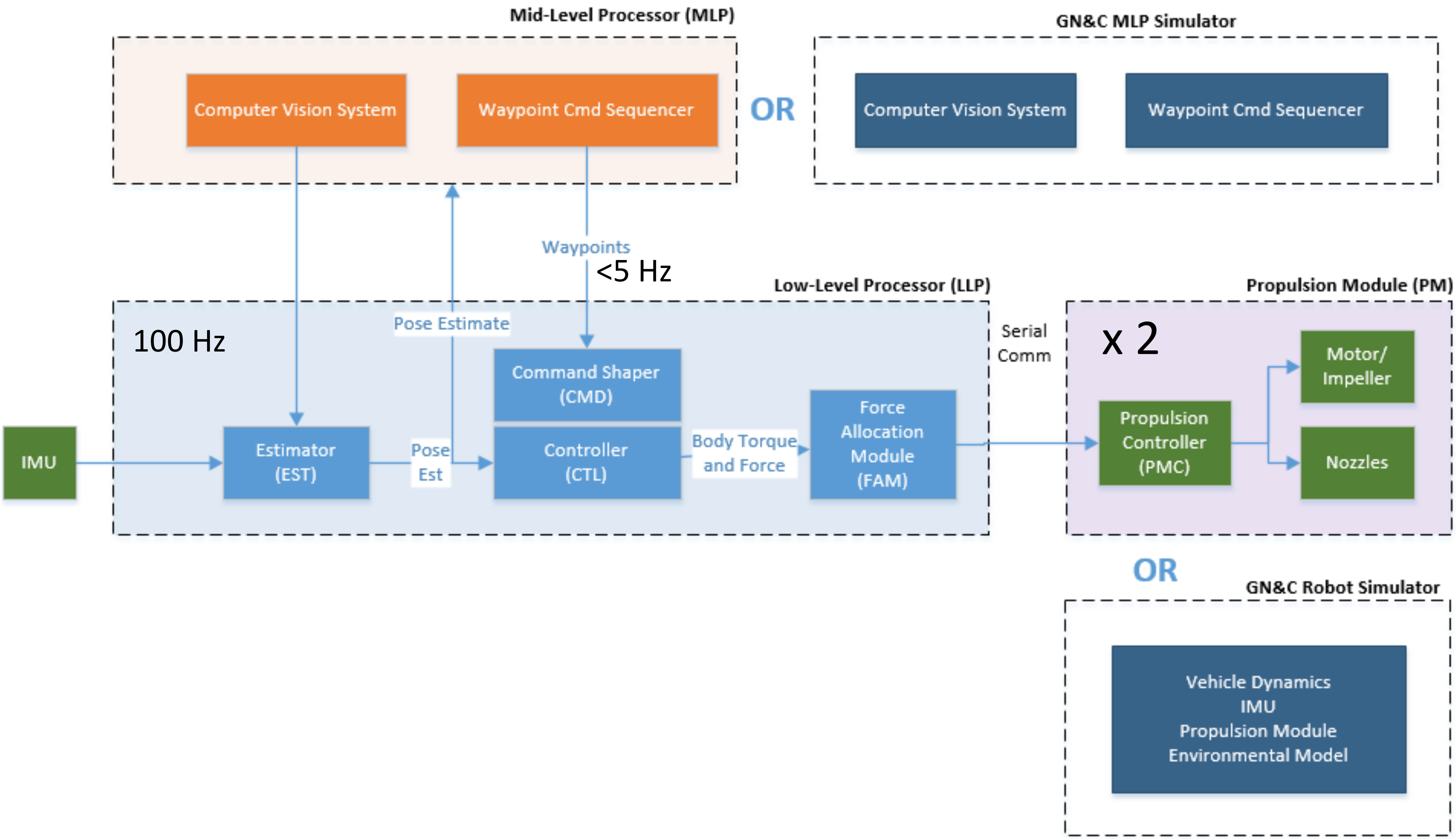
GN&C
Design Drivers

- Utilize vision based navigation
  - Feature recognition for majority of ops space (Nominal)
  - AR targets for docking (Assisted)
  - Optical flow for linear velocity estimates
- Controllability up to 50 cm/s and 45 deg/s
- Achieve max acceleration of 10 cm/s^2 / 10 deg/s^2
- Maintain pose error less than 20 cm / 20 deg (Nominal)
- Maintain pose error less than 2 cm / 8 deg (Assisted)
  - Using artificial landmarks, AR tags, etc.

GN&C
Selected Design

- Estimator and Kalman filter
  - Sensor merging at different update rates
  - Inputs: Vision system, IMU, accelerometers
- Controller
  - PID
- Control Modes
  - Multiple propulsion impeller speeds, depending on performance need

GN&C Architecture Diagram



GN&C
HW Components- IMU

- Epson G362

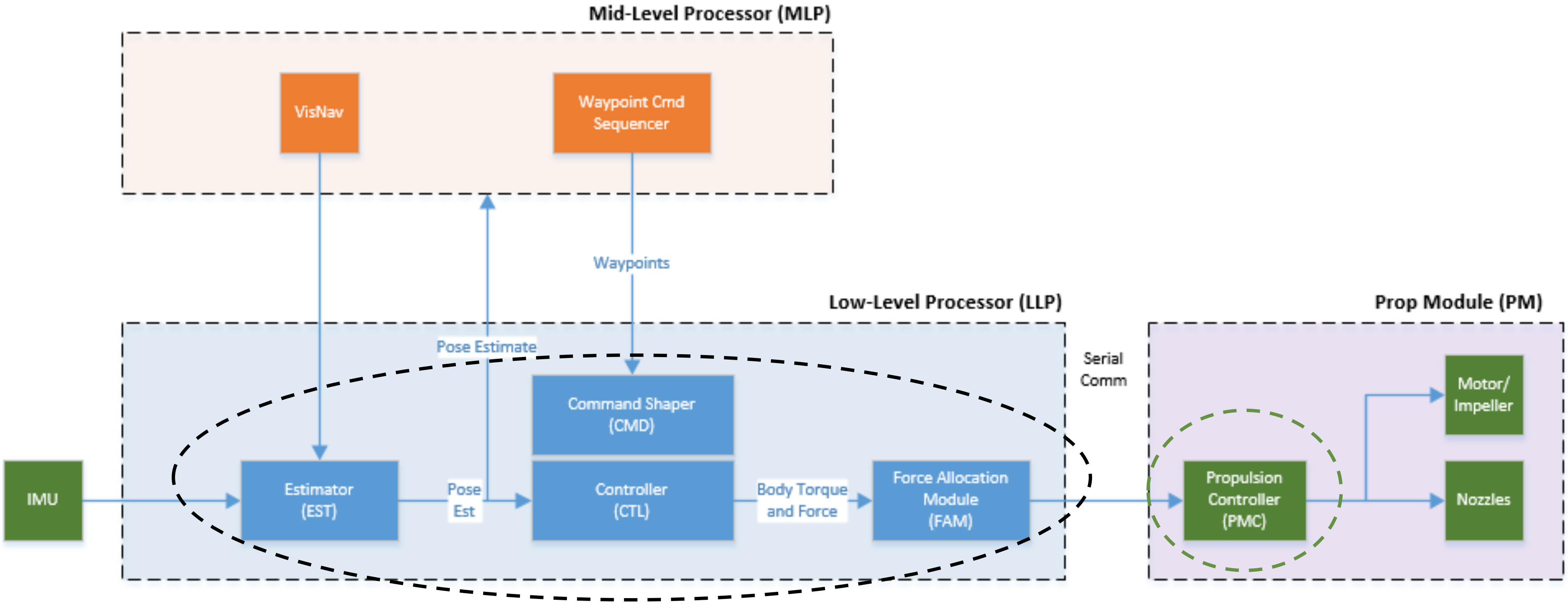
■ FEATURES

- Small Size, Lightweight : 24x24x10mm, 7grams
- Low-Noise, High-stability
  - ➢ Gyro Bias Instability : 3 deg/hr
  - ➢ Angular Random Walk : 0.1 deg/$\sqrt{hr}$
- Initial Bias Error : ±0.5 deg/s (1σ)
- 6 Degrees Of Freedom
  - ➢ Triple Gyroscopes : ±150 deg/s,
  - ➢ Tri-Axis Accelerometer : ±3 G
- 16/32bit data resolution
- Digital Serial Interface : SPI / UART
- Calibrated Stability (Bias, Scale Factor, Axial alignment)
- Data output rate : to 2k Sps
- External Trigger Input / External Counter Reset Input
- Calibration temperature range : −20°C to +70°C
- Operating temperature range : −40°C to +85°C
- Single Voltage Supply : 3.3 V
- Low Power Consumption : 30mA (Typ.)

Other IMUs ruled out in trade study:

- Epson G350
  - 2x bias and random walk
- SBG Ellipse
  - Performance similar to G350
  - Un-needed integrated Kalman filter
  - Non-transparent documentation

GN&C Software Components



Components

- Estimator (EST)
- Command Shaper (CMD)
- Control (CTL)
- Force Allocation Module (FAM)
- Propulsion Module Controller (PMC)

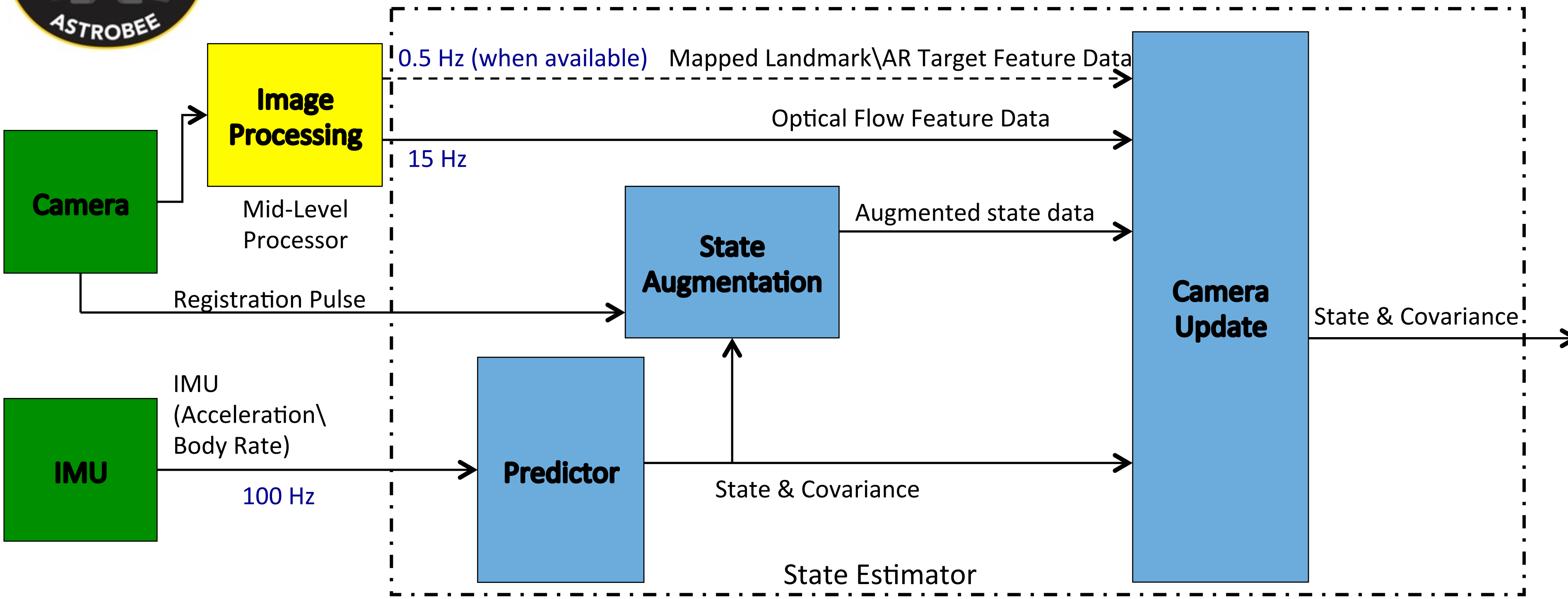
Integration with FSW

- All GN&C software components are auto-coded and imported into a single high priority ROS node.
- There is a single thread inside that node that represents a highest priority 100 Hz execution loop.

GN&C: SW Components Estimator (EST)

- State Estimator Utilizes an Extended Kalman Filter with Augmented States to account for the large time delays inherent to vision navigation systems
- Fuses data from several disparate sources and update rates
  - IMU data is updated at 100 Hz with negligible delay
  - Optical flow data is received at 15 Hz with small delays
  - Mapped landmark data is received at .5 Hz with large (~2 Seconds) delays
  - AR Target data is received at 5 Hz with small delays
- An augmented state vector is utilized in the estimator to deal with the delayed vision based measurements:
  - Covariance and the current state estimate are captured at the moment the camera takes a picture (via a registration pulse)
  - Once the image is processed, the reduced data is sent to the estimator but with significant delays (up to 2 seconds).
  - Errors in the state estimate at the time the image was taken are used to infer current state errors

GN&C: SW Components Estimator (EST) – Cont.



- IMU data is used to replace a dynamics model in the predictor, which allows for:
  - Changes to the physical properties of AstroBee
  - Non-actuated pose determination
- Vision data uses the augmented state to calculate errors at the time the image was taken
  - Accommodates large sensor delays
- In nominal operations the mapped landmark features are compared against a map of ISS, optical flow allows the system to move through areas where no features are recognized
- When docking the AR Target features replace the mapped landmark features inside the estimator

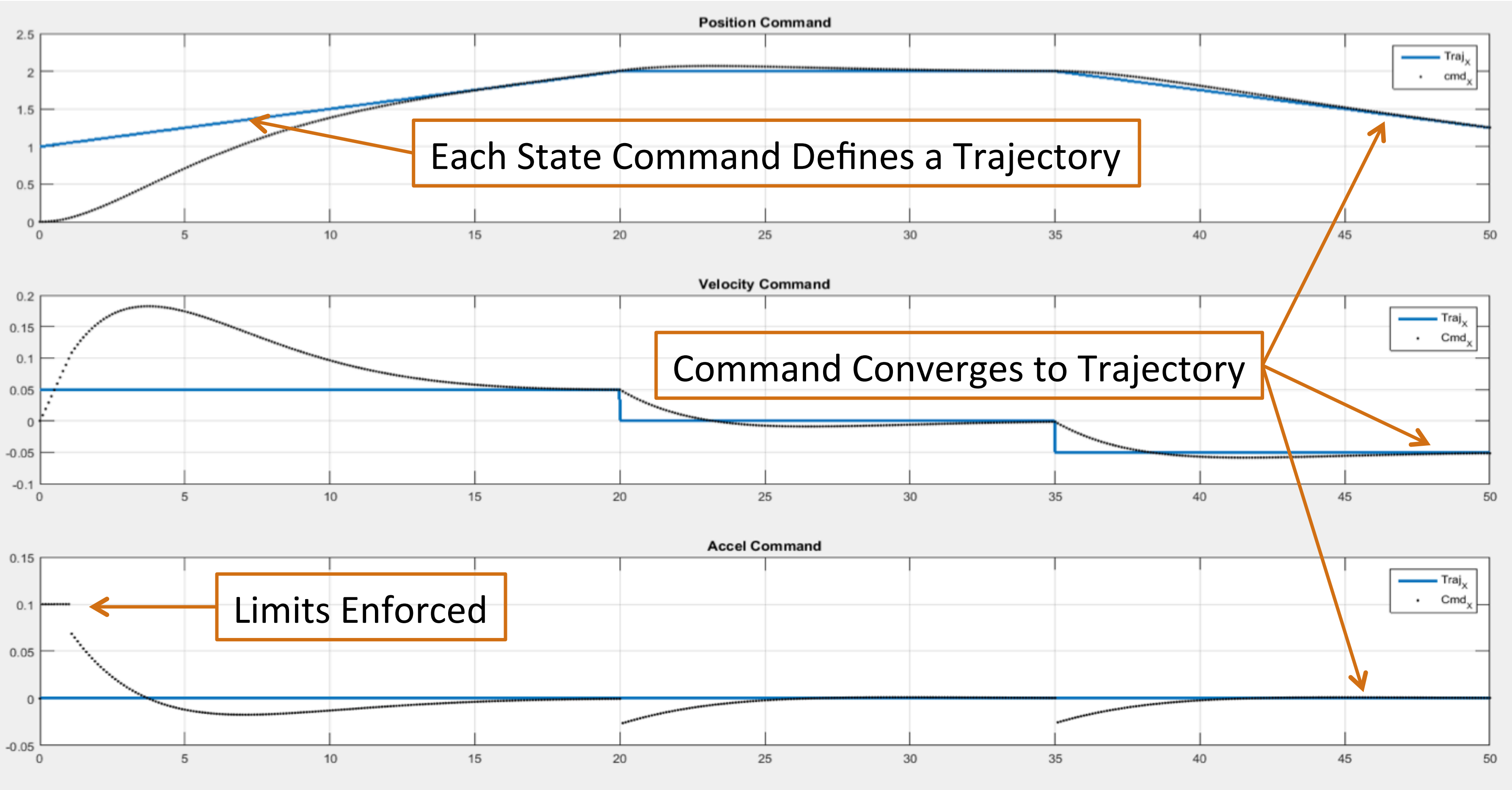
GN&C: SW Components Command Shaper (CMD)

1D State Command Example:

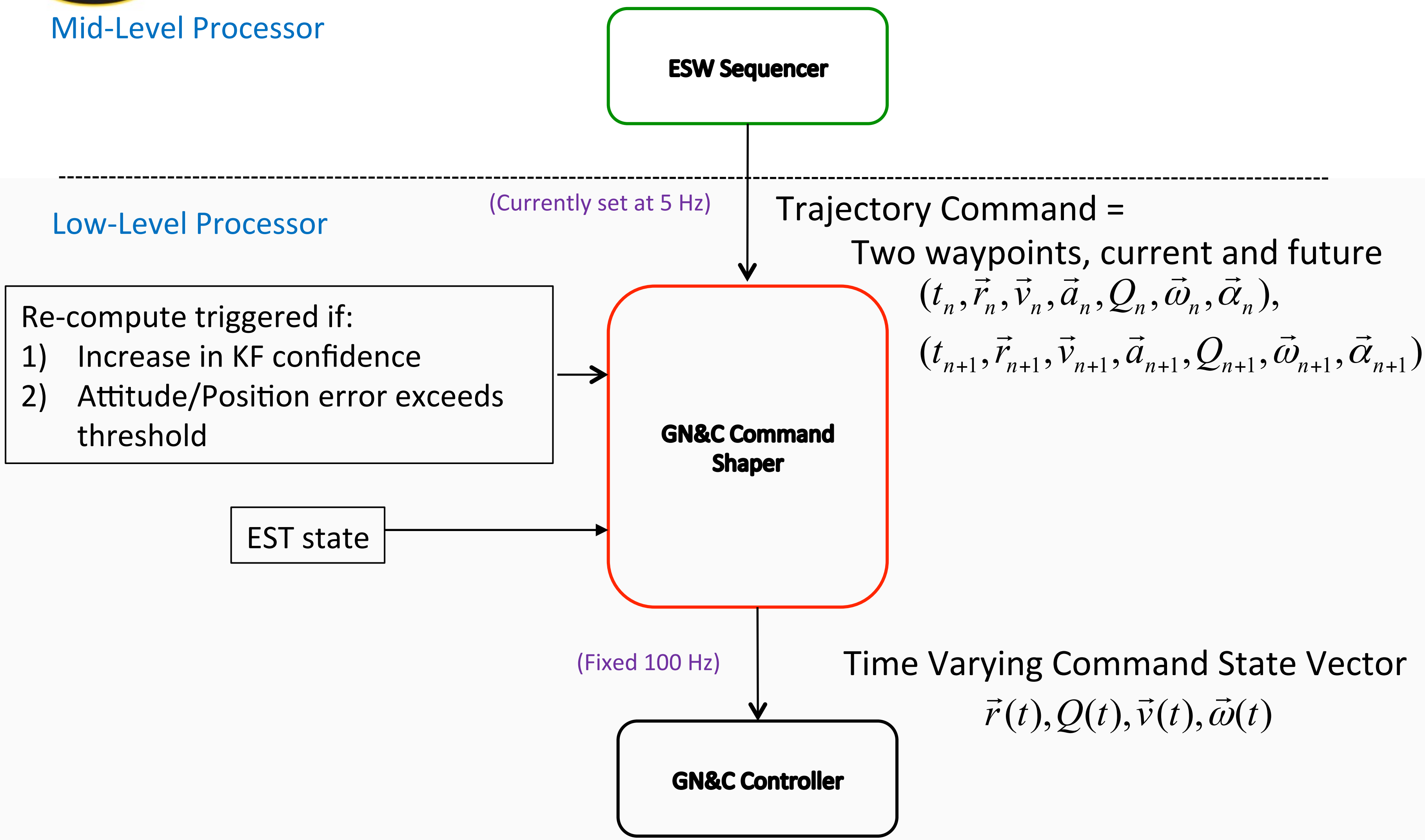
Command 1: Time = 00, Position = 1, Velocity = .05, Accel = 0

Command 2: Time = 20, Position = 2, Velocity = .00, Accel = 0

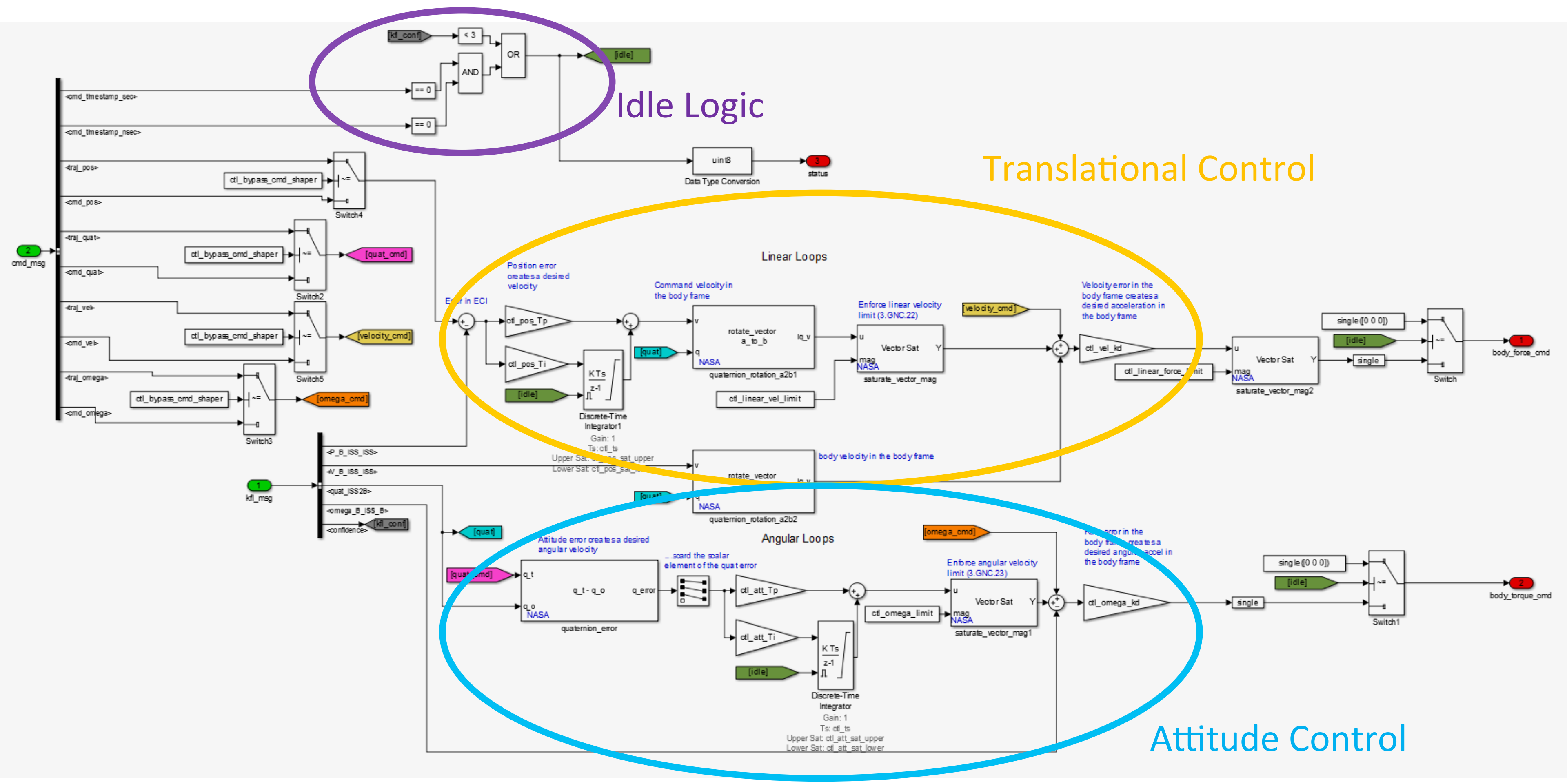
Command 3: Time = 35, Position = 2, Velocity = -.05, Accel = 0



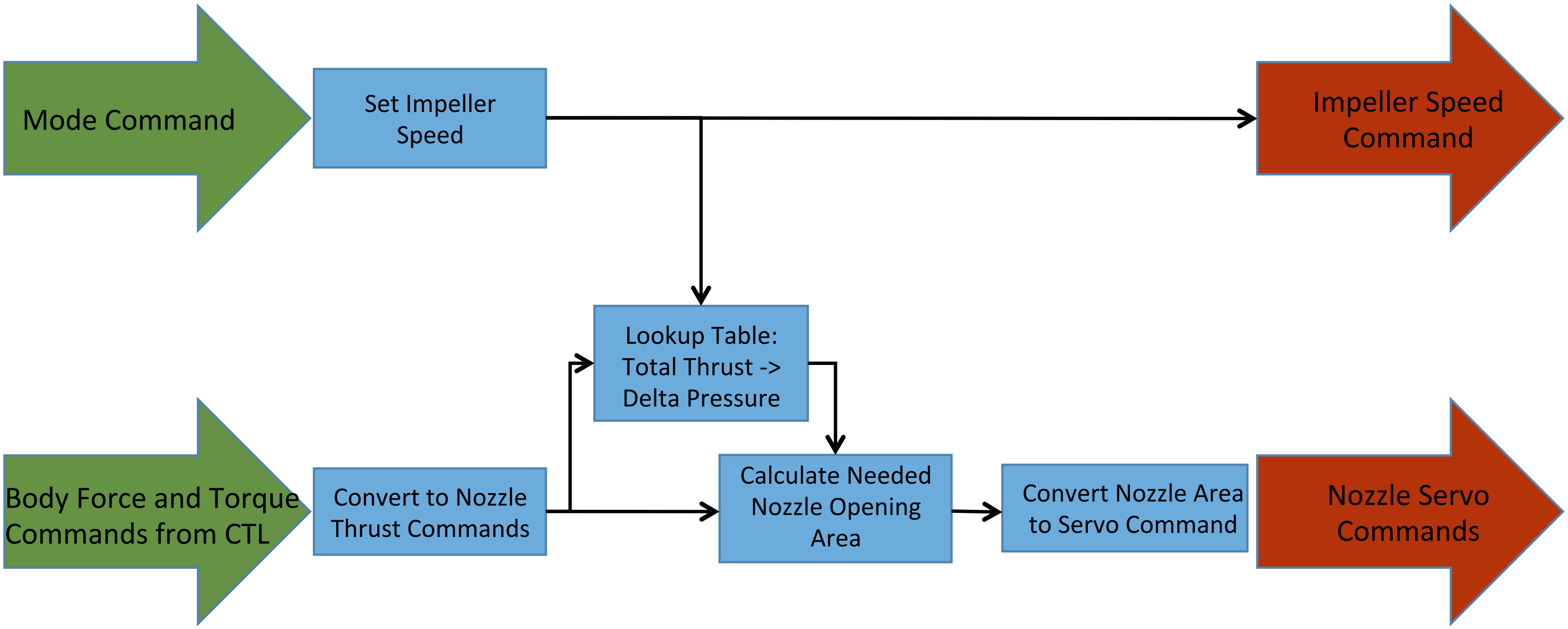
GN&C: SW Components
Command Shaper (CMD)



GN&C: SW Components
Control (CTL)



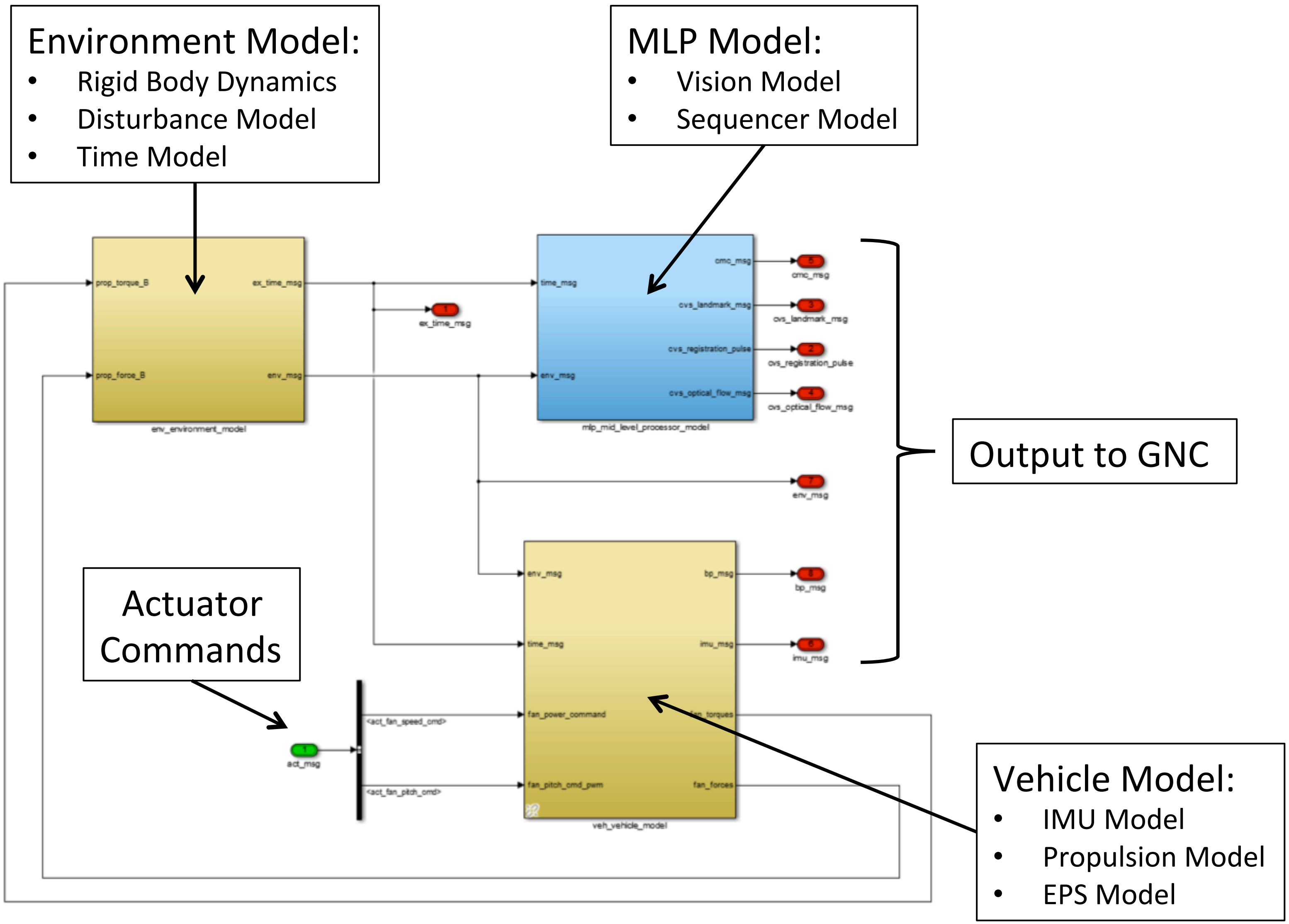
GN&C: SW Components
Force Allocation Module (FAM)



GN&C Simulation Model

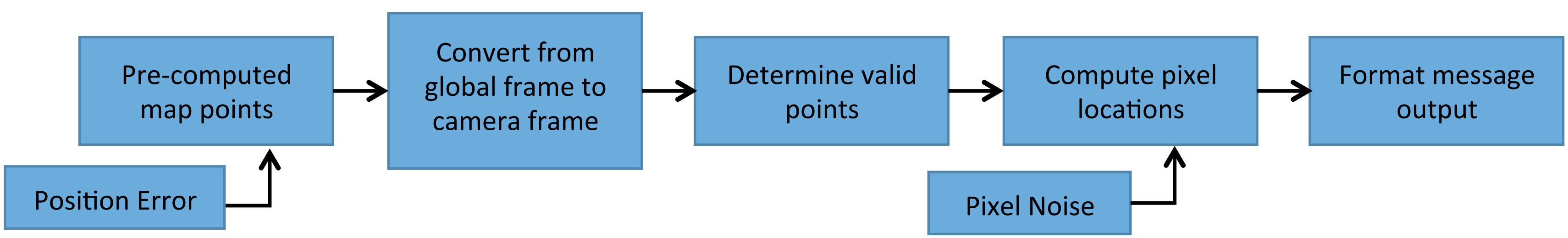
- Models developed for simulation:
  - IMU
  - Vision system
  - Propulsion system (motor, impellor, plenum, nozzles, nozzle servos)
  - Electrical power system
  - MLP sequencer
  - Rigid Body Dynamics (both a flight and a granite table version)
- Uses
  - Control and estimator algorithm development
  - Software testing
  - Control robustness analysis(linear analysis and Monte Carlo testing)
  - Trade study analysis tool
  - Testing of sortie scenarios
  - Requirements verification (where ground testing is not possible)

GN&C Simulation Model

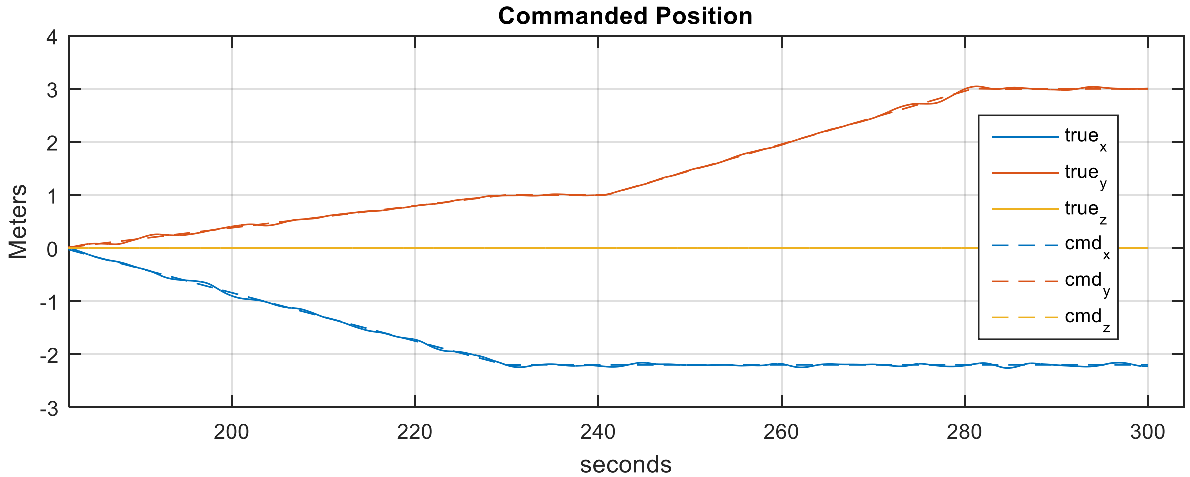


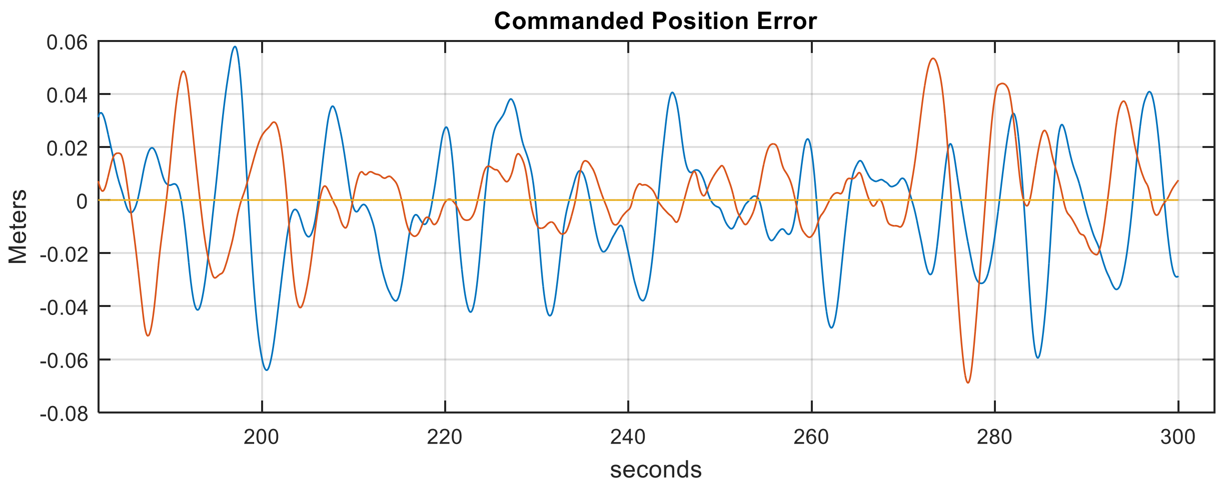
GN&C
Vision Model

- Models the landmark, AR tag and optical flow output from the MLP
- Pre-computed map points (separate for landmarks vs AR tags vs optical flow) can be randomly generated, or imported from an actual map
- Current model assumptions:
  - Resolution: 1280x960 pixels
  - Field of View: 60 degree half angle
  - Max error on mapped points: < 5cm
  - Max noise on pixel locations: < 2 pixels
  - Landmark image processing time: 0.5 sec (2 Hz)
  - Optical flow image processing time: 0.07 sec (~15Hz)
  - AR tag image processing time: 0.17 sec (~6Hz)
- Limitation: Camera model does not recreate the fish eye distortion



GN&C
Simulation Results





True Position Error Stats:
Max Error (m): -0.074351, -0.068885, 0.000000
Mean (m): -0.005970, 0.000987, 0.000000
Mean + 3 Sigma (m): 0.073284, 0.051370, 0.00000

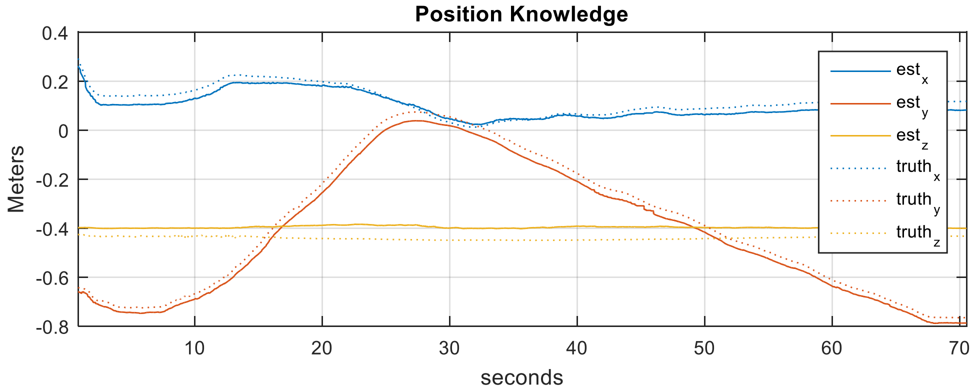
True Attitude Error Stats:
Max Error (deg): 0.634271
Mean (deg): 0.217365
Mean + 3 Sigma (deg): 0.629915

Position Knowledge Error Stats:
Max Error (m): -0.040977, -0.144290, 0.089682
Mean (m): 0.000022, 0.000594, 0.000066
Mean + 3 Sigma (m): 0.034033, 0.042330, 0.0397

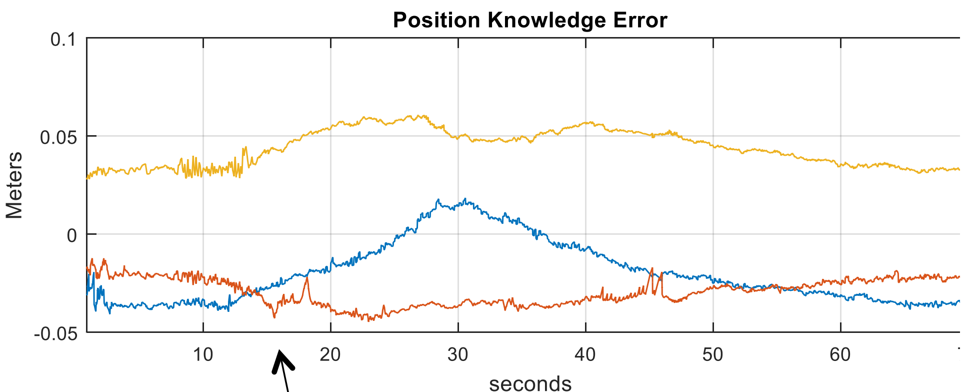
Velocity Knowledge Error Stats:
Max Error (m/s): 0.045546, -0.194909, 0.095848
Mean (m/s): 0.000026, -0.000330, -0.000085
Mean + 3 Sigma (m/s): 0.043464, 0.033258, 0.025

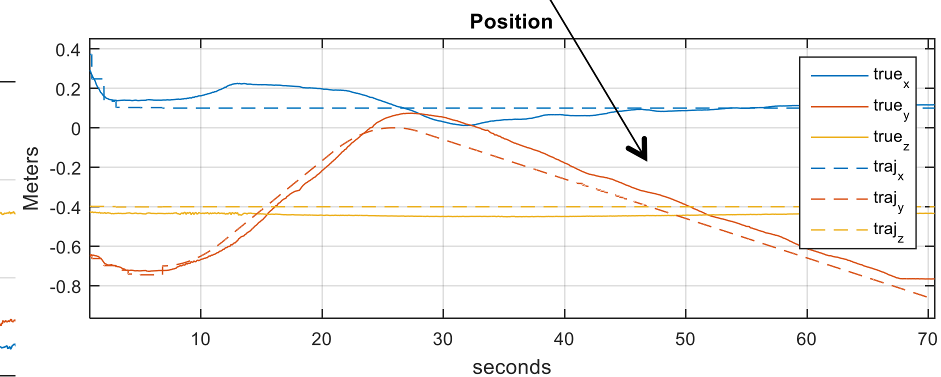
Attitude Knowledge Error Stats:
Max Error (deg): 0.539591
Mean (deg): 0.145368
Mean + 3 Sigma (deg): 0.396710

GN&C
Granite Table Test Results

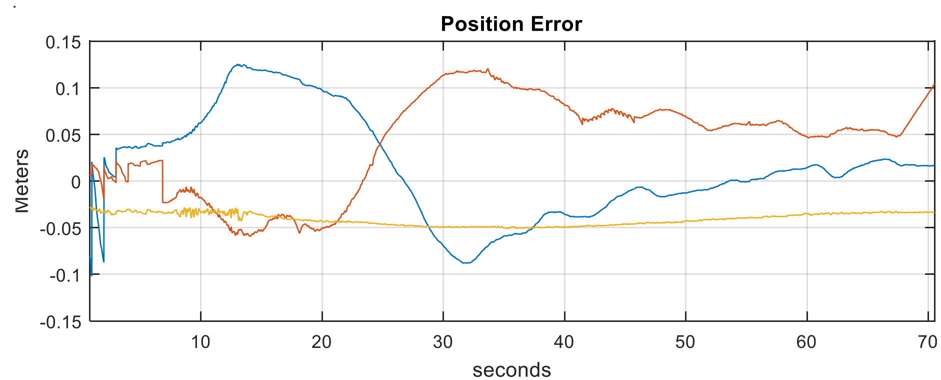


Constant offset errors in control system are present due to difficulties in maintaining calibration of the variable pitch propeller system





AR Target localization system performing well in granite table test (low knowledge errors)



Backup Slides

GN&C
Fault Management

1. Attitude/Position error exceed threshold:
   - Possible causes: External disturbance force
   - Ramification: Large errors seen by controller
   - Response: Re-compute time varying command state vector
2. Estimator Diverges:
   - Possible causes: Conflicting sensor measurements, etc.
   - Ramification: Loss of pose knowledge
   - Response: ??
3. MLP Commanded soft-stop:
   - Possible cause: Fault detected by MLP
   - Ramification: Need to come to a stop
   - Response: Mode change
4. Sensor Faults:
   - Possible cause: Fault detected in sensor
   - Ramification: Possible incorrect sensor data
   - Response: ??
5. Other

GN&C: SW Components
Propulsion Module (PM)

- **Motor**: Maxon EC45 Flat, 30W
- **Motor drive**: Maxon ESCON Module 24/2
  - 4-Q servo controller for DC/EC motors
  - 2/6 A, 10-24 VDC
- **Nozzle servo**: MKS DS92A+
- **Propulsion Controller** (PMC)
  - 32-bit microcontroller: Microchip PIC32MX795F512H
  - Development environment: MPLAB X IDE v3.10
  - Comm with LLP: I2C bus
  - Impeller motor speed control: Analog voltage
  - Nozzle position control: PWM signal, 333hz data, pulse width of 850µs~2150µs

GN&C
Test Plan – Performance Verification

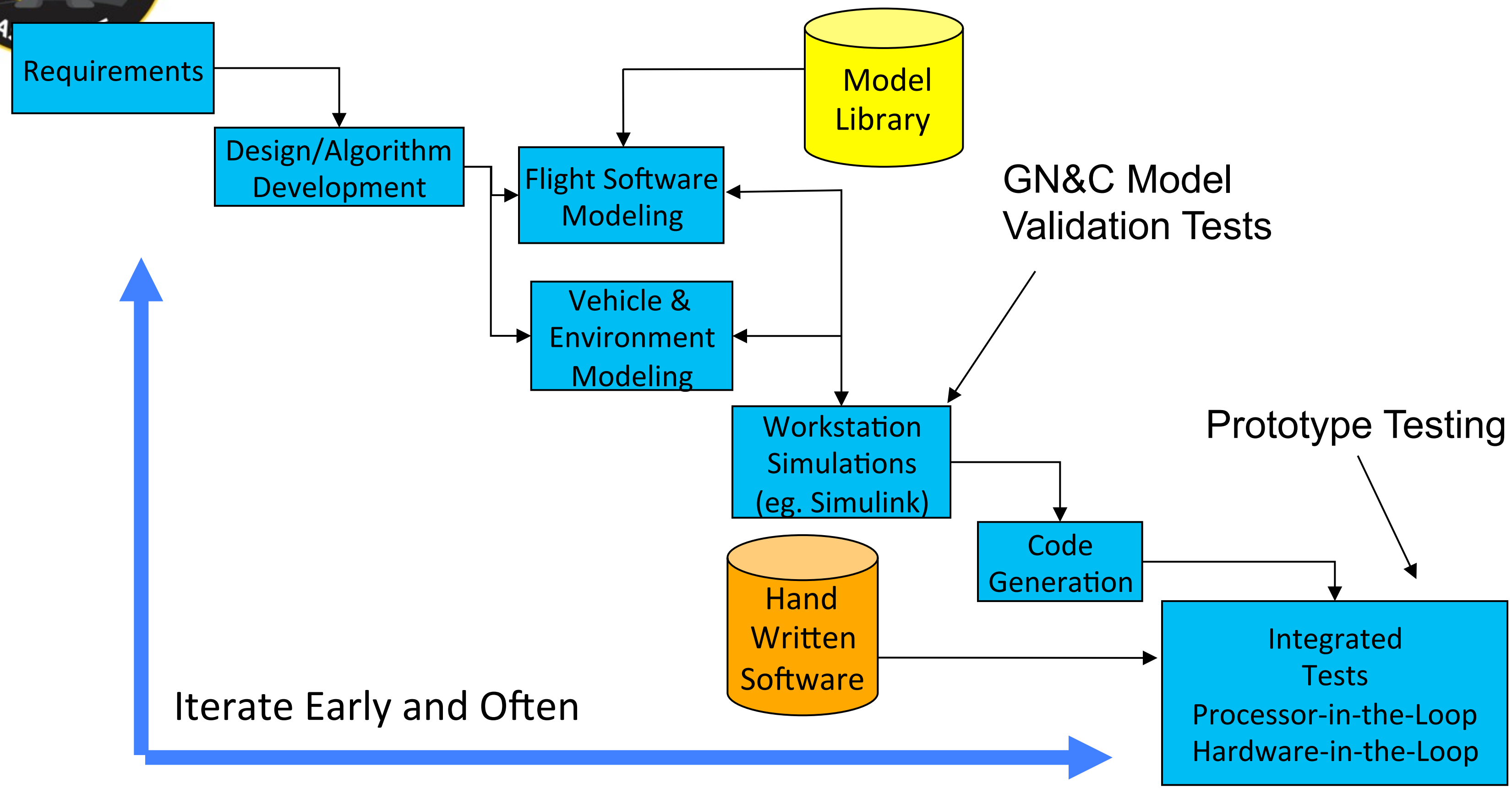
- Granite Table (open and closed loop)
  - Multiple mounting orientations on airbearing
  - Characterizes undesired coupling of axes

- Gantry + Active Gimbal System (open loop)
  - Follow predetermined trajectories and evaluate pose estimate for accuracy
  - Challenges still exist regarding pendulum motion

- (Goal) Gantry + Active Gimbal System (closed loop)
  - Attitude control loop will be closed through the Gantry + Gimbal system to achieve the desired robot motion.
  - Blower speeds and nozzle settings be forwarded to an external system that will model the robot dynamics and calculate the resultant pose of the robot in space.
  - This pose will be commanded to the Gantry + Gimbal system.

- High Speed Test on Smooth Floor or Cart (closed loop)

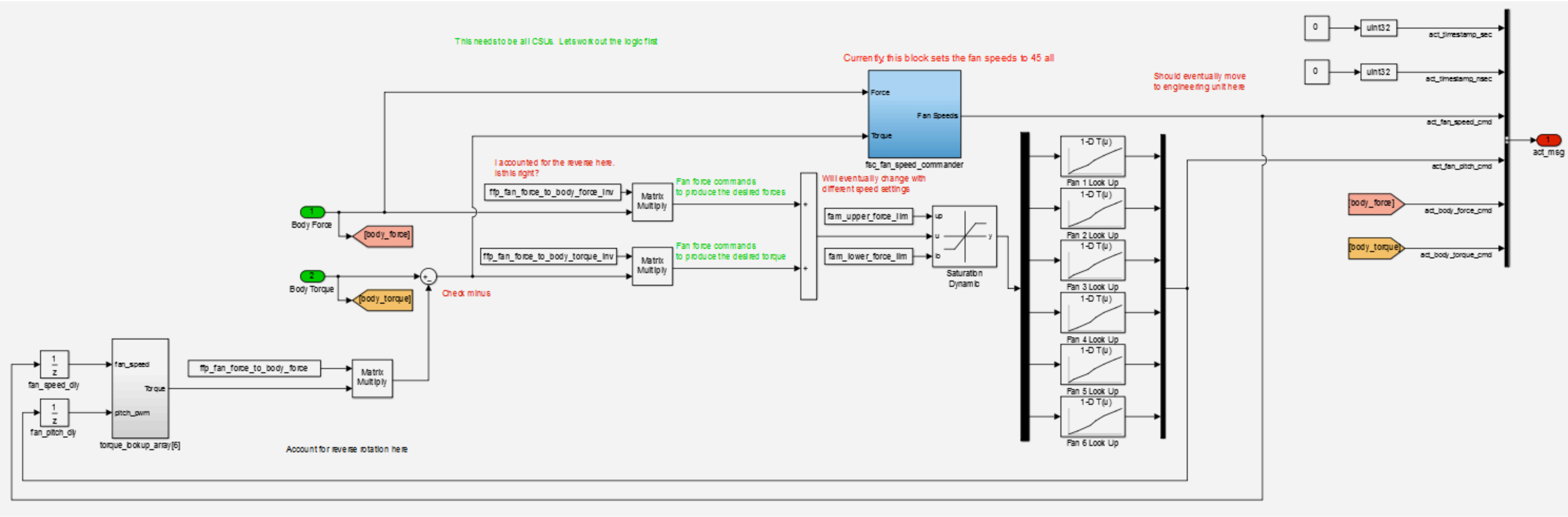
GN&C
Model based design approach



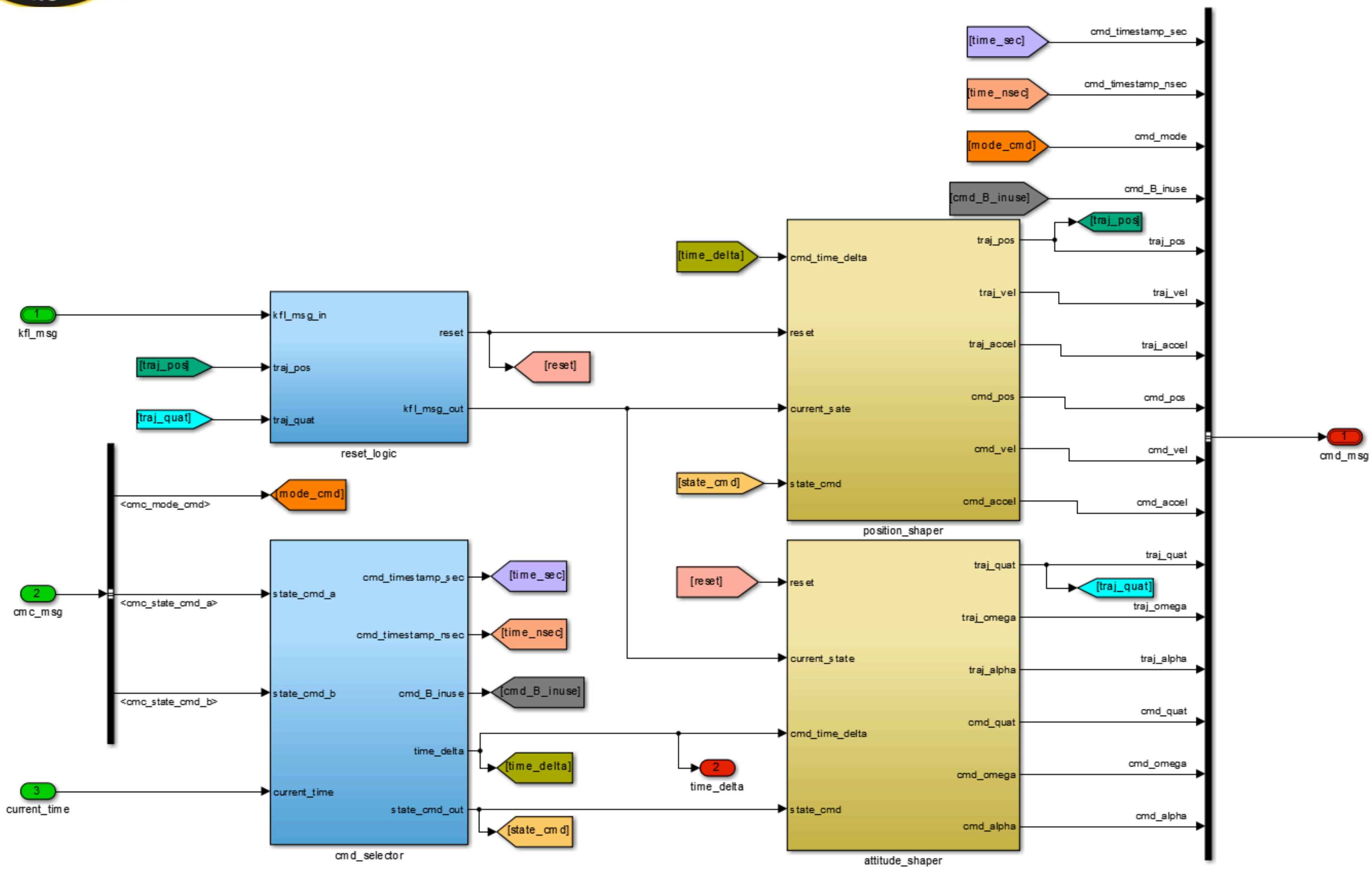
1. Modification of the LADEE GN&C software development approach
2. Develop models of FSW, robot, and environment in Simulink
3. Auto-generation of source code using RTW/EC
4. Integrate with hand-written software
5. Iterate while increasing fidelity of tests – workstation simulation and prototype testing

GN&C: SW Components
Force Allocation Module (FAM)

Proto3 Design (VPP)



GN&C: SW Components
Command Shaper (CMD)



Astrobee Perching Arm

Design Overview

Team

- In Won Park (ARC-TI)
- Matei Ciocarlie (Columbia Univ.)
- Jongwoon Yoo (ARC-TI)
- Ted Morse (ARC-TI)
- Dong-Hyun Lee (ARC-TI)

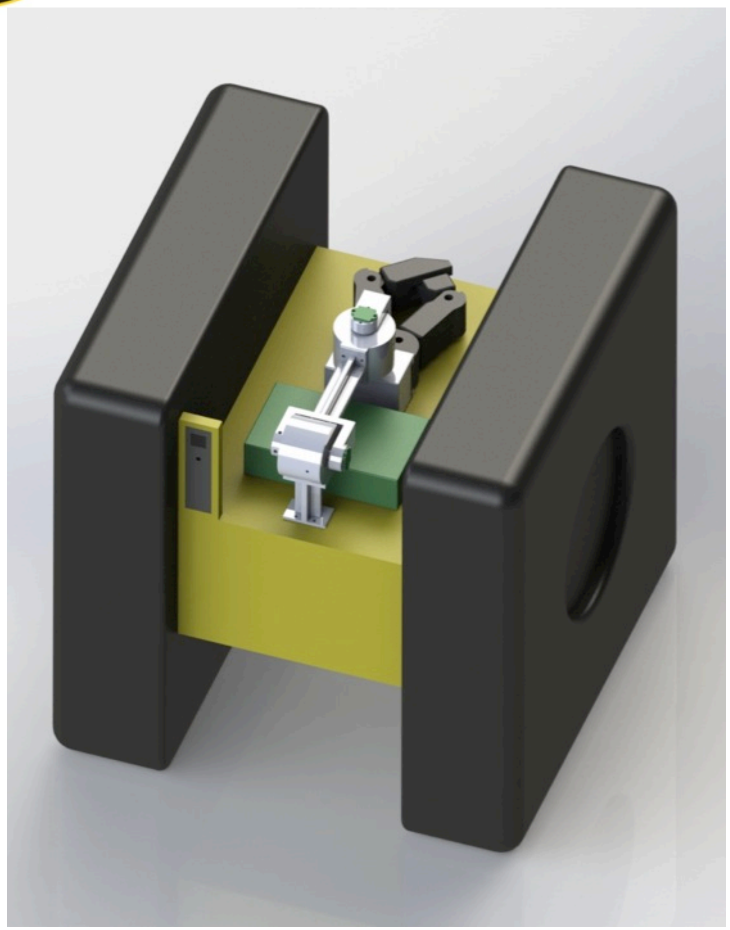
Status - Summary

or Proto 4 Item	Status
Design and fabricate arm	Will be complete
Design and fabricate gripper	Will be complete
Select DC motor and bearing	Complete
Select magnetic encoder for absolute position	Complete
Select structural material	Will be complete
Design controller board	Will be complete
Select microcontroller	Complete
Select motor driver	Complete
Develop firmware for controller board	Will be complete
Develop simulation model in ROS/Gazebo	Complete

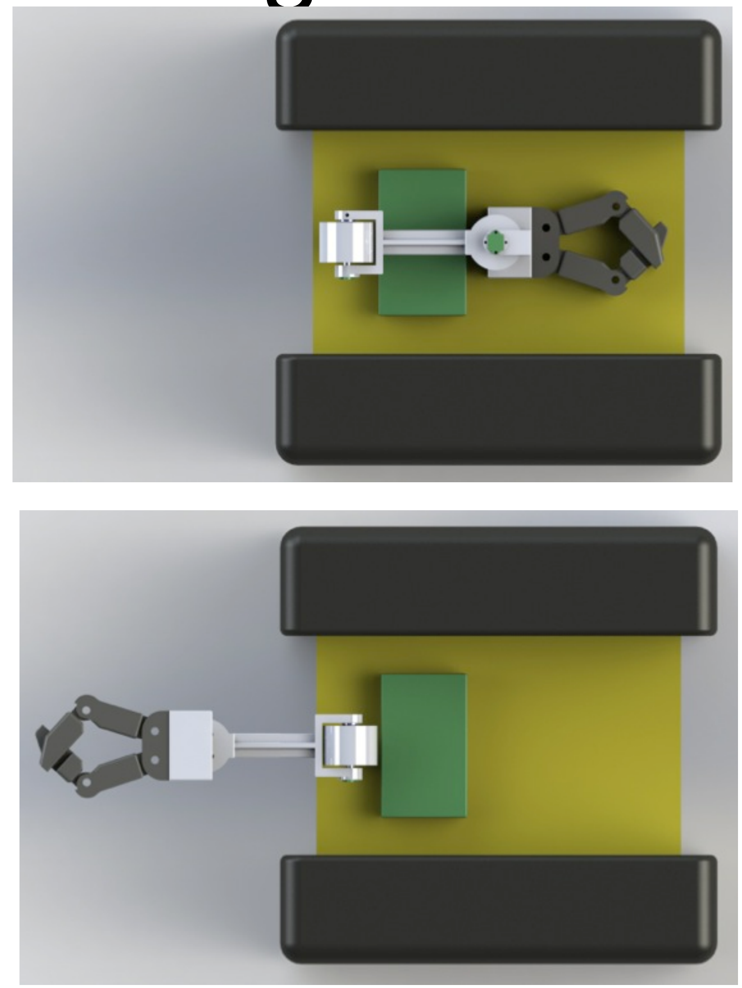
Design Drivers

- Lightweight, small, and compliant
  - Mass budget = 200 g
  - Volume = 150 mm x 254 mm x 100 mm
    - Able to stow inside the robot so that it is not exposed to collision hazard while stowed
    - Able to operate as a pan-tilt module for a camera attached on the opposite side of the robot to support remote monitoring operations
  - Arm joints should be fully back-drivable and gripper should be released automatically when it detects large astronaut-induced torques
  - Gripper should be released manually by the astronaut

Mechanical Design

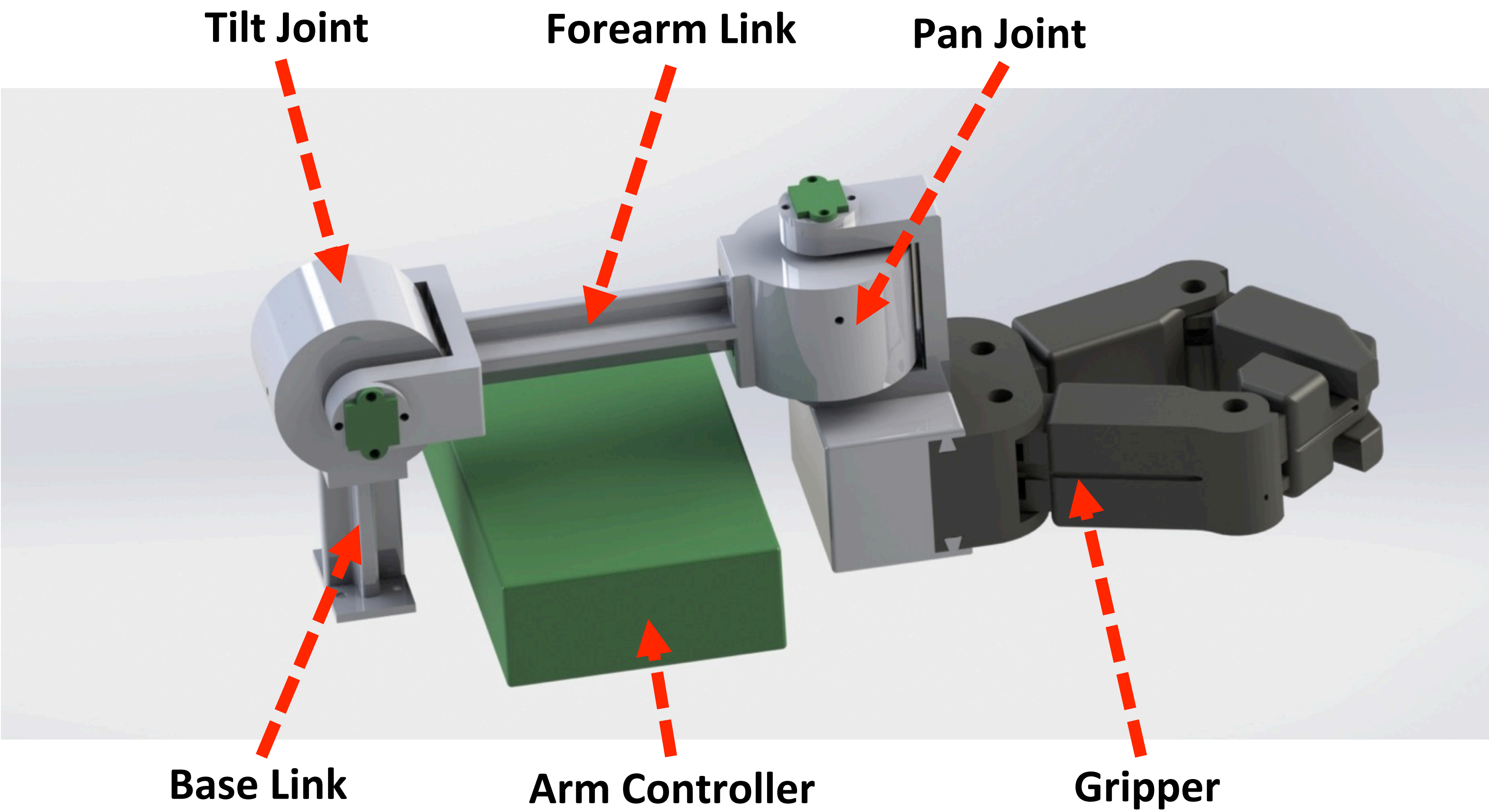


Stowed Configuration
(diagonal view)

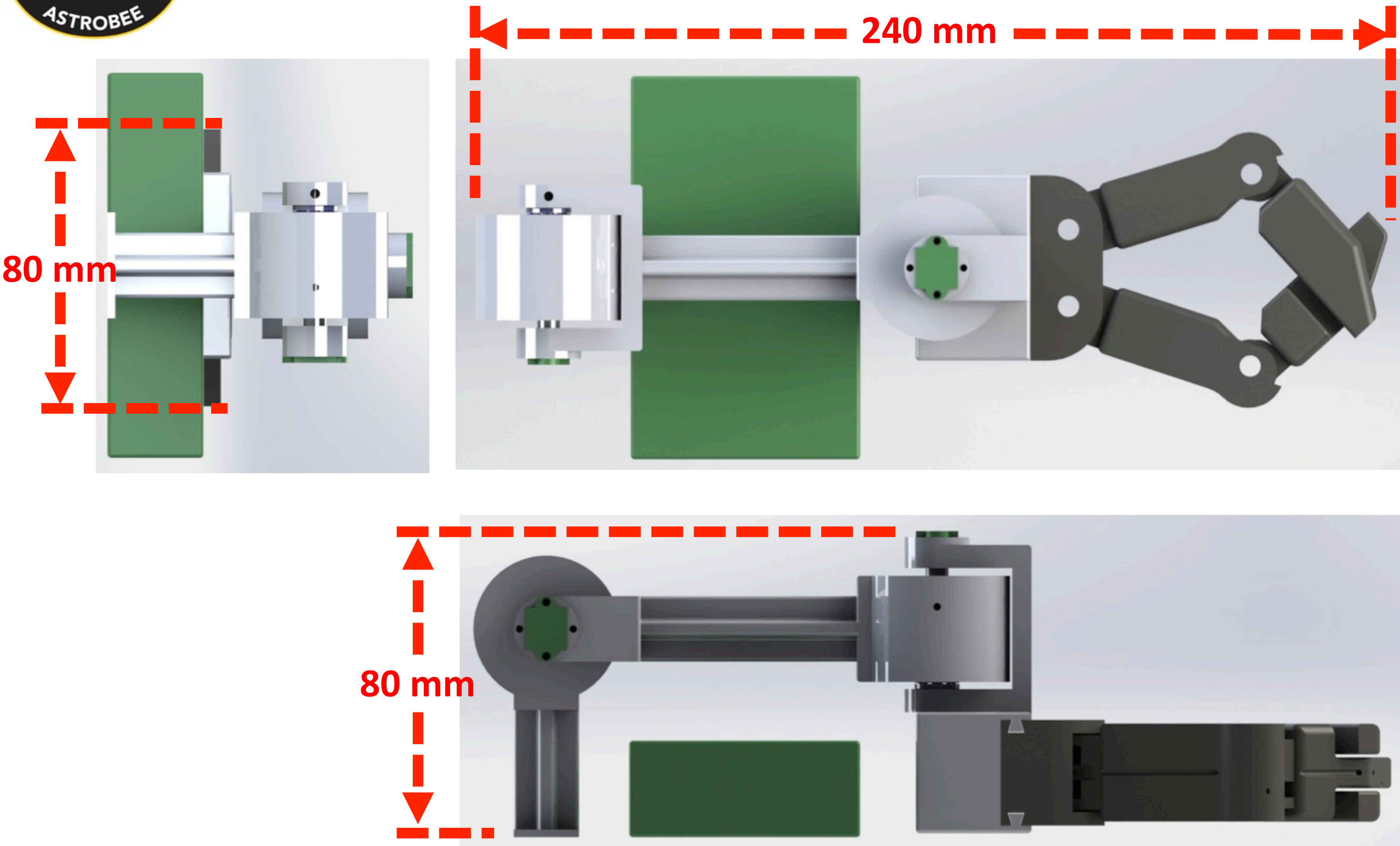


Stowed/Deployed Configuration
(top view)

Mechanical Component



Mechanical Dimension



Mechanical Mass

	Base Link	Tilt Joint	Forearm Link	Pan Joint	Gripper	Total [g]	Note
Aluminum	14.89	102.18	21.95	103.84		242.86	0.002712 g/mm^3
Ultem 2300	8.29	68.86	12.22	69.78		159.15	0.00151 g/mm^3
Ultem 9085	7.36	64.15	10.85	64.97		147.33	0.00134 g/mm^3
Plastic					110.00	110.00	From P3 gripper
1. Aluminum Case Arm + Plastic Case Gripper						352.86	
2. Ultem 2300 Case Arm + Plastic Case Gripper						269.15	
3. Ultem 9085 Case Arm + Plastic Case Gripper						257.33	

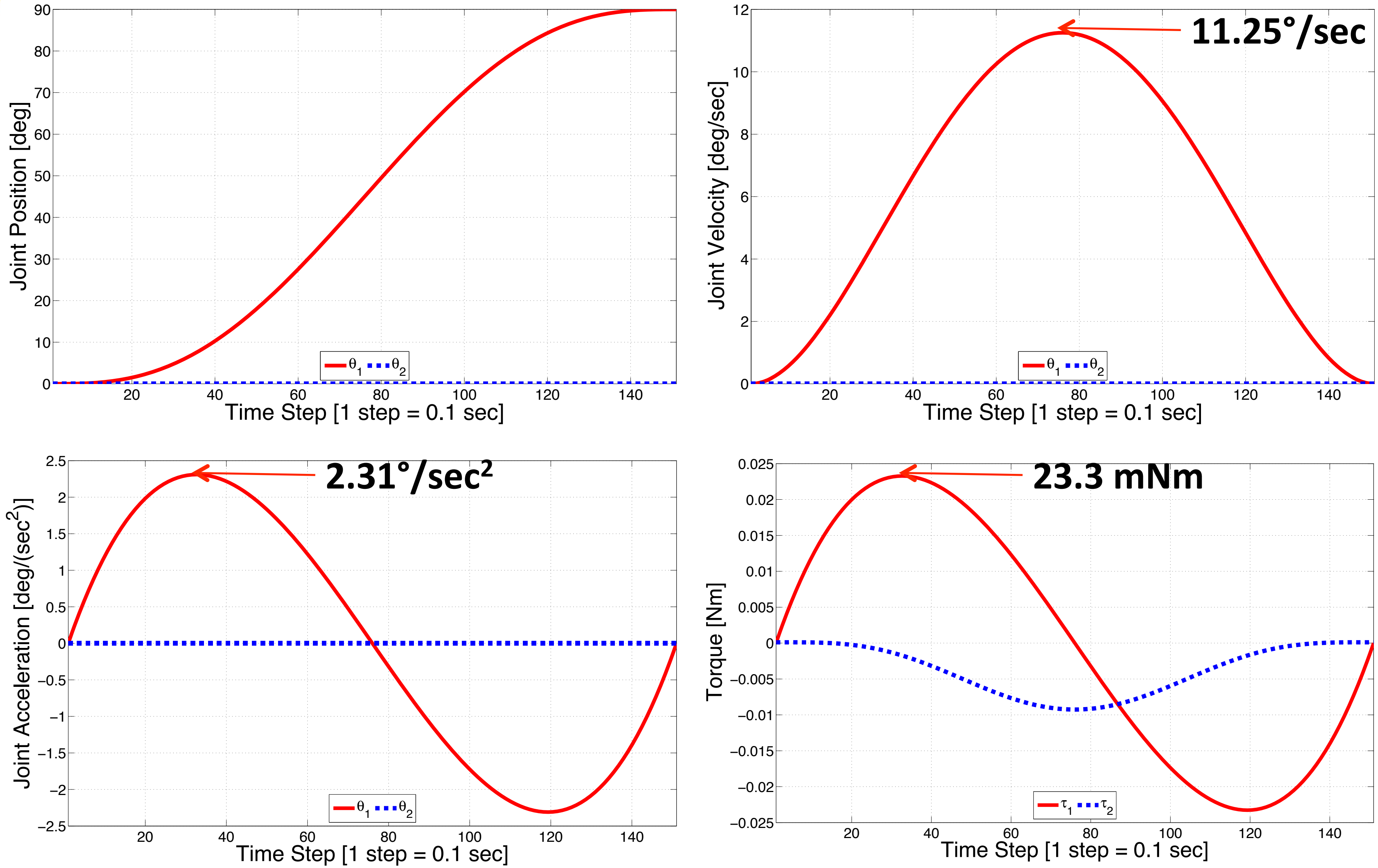
- The mass of bearing, bolt, connector board and electrical wire has not been added

Motor Selection

- MATLAB Robotics Toolbox is used to obtain kinematics and dynamics
  - Assumed point mass with 6 kg of Astrobee structural mass
  - Assumed micro-gravity environment (9.8E-6 m/s^2)
- Minimum-jerk trajectory is used to obtain position/velocity/ acceleration trajectory

✔ [FFREQ-175] *The perching arm shall pan/tilt 90 degrees in 15 seconds.*

Motor Selection



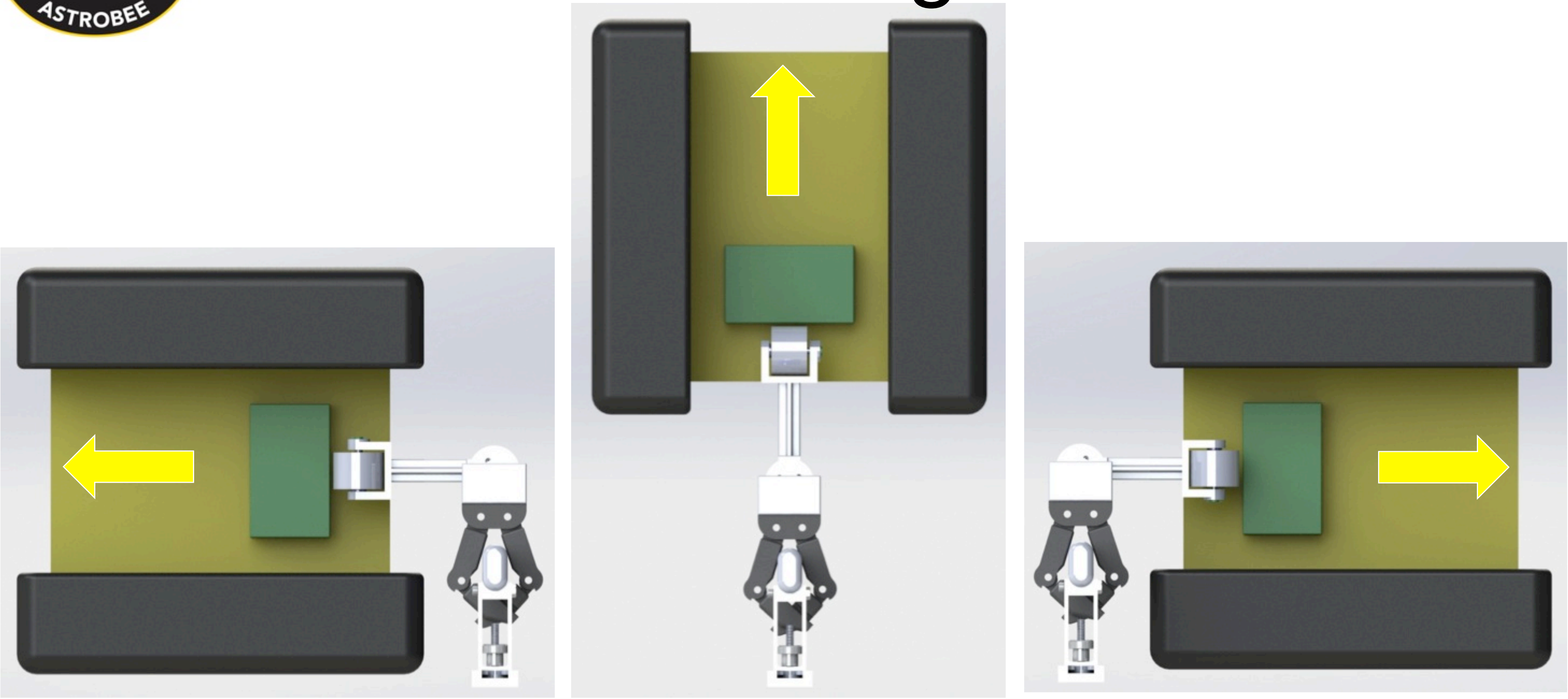
Motor Selection

- Faulhaber 2619
  - Diameter 26 mm, length 21.5 mm
  - Input voltage = 6V
  - Encoder resolution = 0.05 °/Tick

Specifications

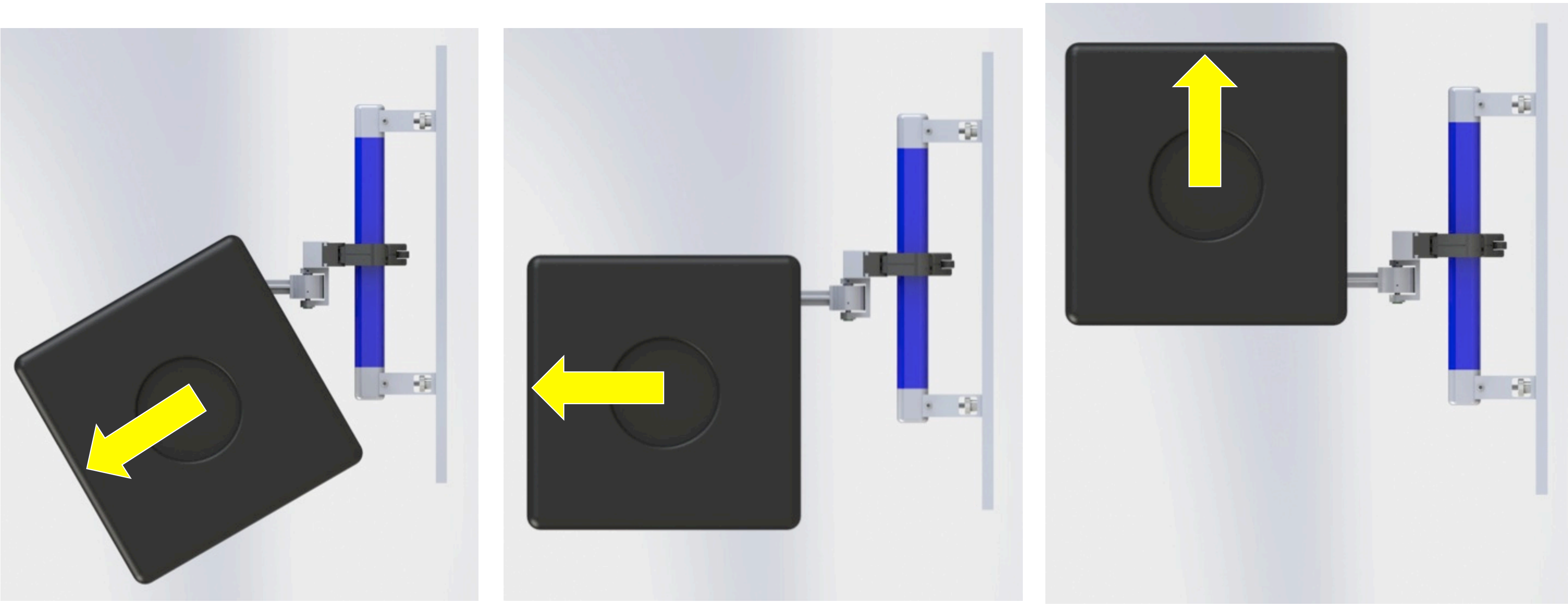
reduction ratio (rounded)	output speed up to n_{max} rpm	weight with motor g	output torque continuous operation M_{max} mNm	output torque intermittent operation M_{max} mNm	direction of rotation (reversible)	efficiency %
8 : 1	635	25	9	30	=	81
22 : 1	223	26	23	75	≠	73
33 : 1	151	26	30	100	=	66
112 : 1	44	27	93	180	≠	59
207 : 1	24	27	100	180	=	53
361 : 1	14	27	100	180	=	53
814 : 1	6	28	100	180	=	43
1 257 : 1	4	29	100	180	=	43

Pan Range



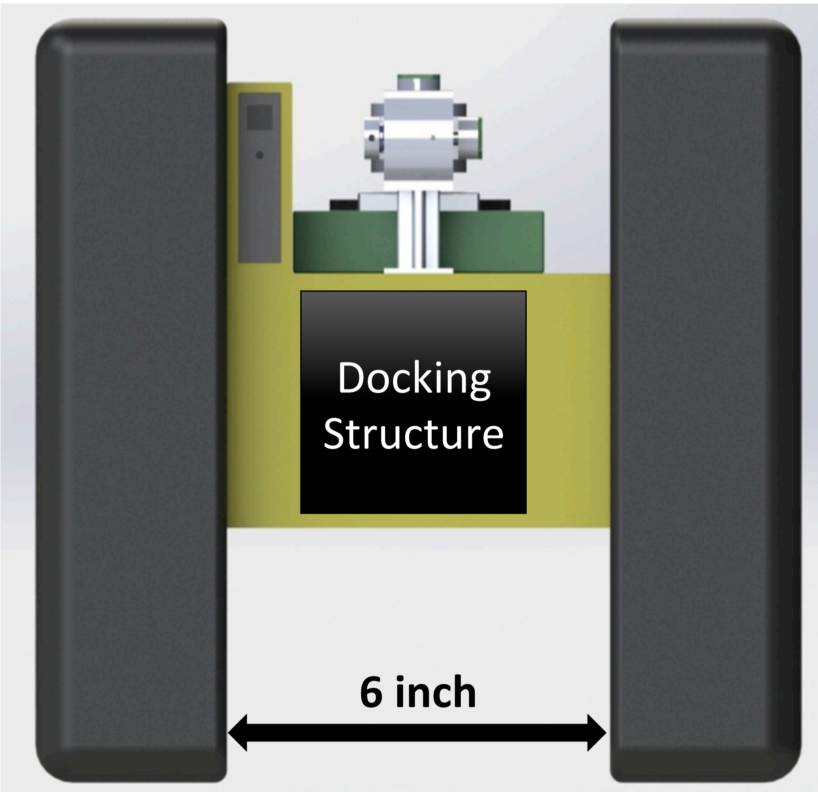
✔ [FFREQ-175] *The perching arm shall pan at least -90° to 90° out from center while perched.*

Tilt Range



✔ [FFREQ-175] *The perching arm shall tilt at least -30° to 90° out from center while perched.*

Perch Cam Location



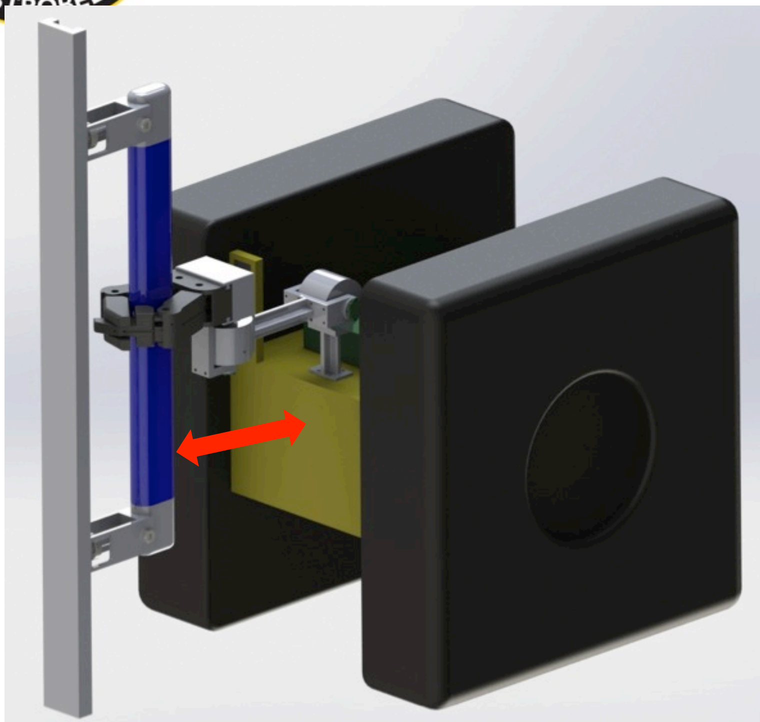
Front View

✔ [FFREQ-185] *The perching arm shall be within the view range of perching camera when the arm is deployed.*

- To meet this requirement, the perch camera must be placed in 'Aft Top Bay' on the side of docking structure.

CamBoard Pico Flexx

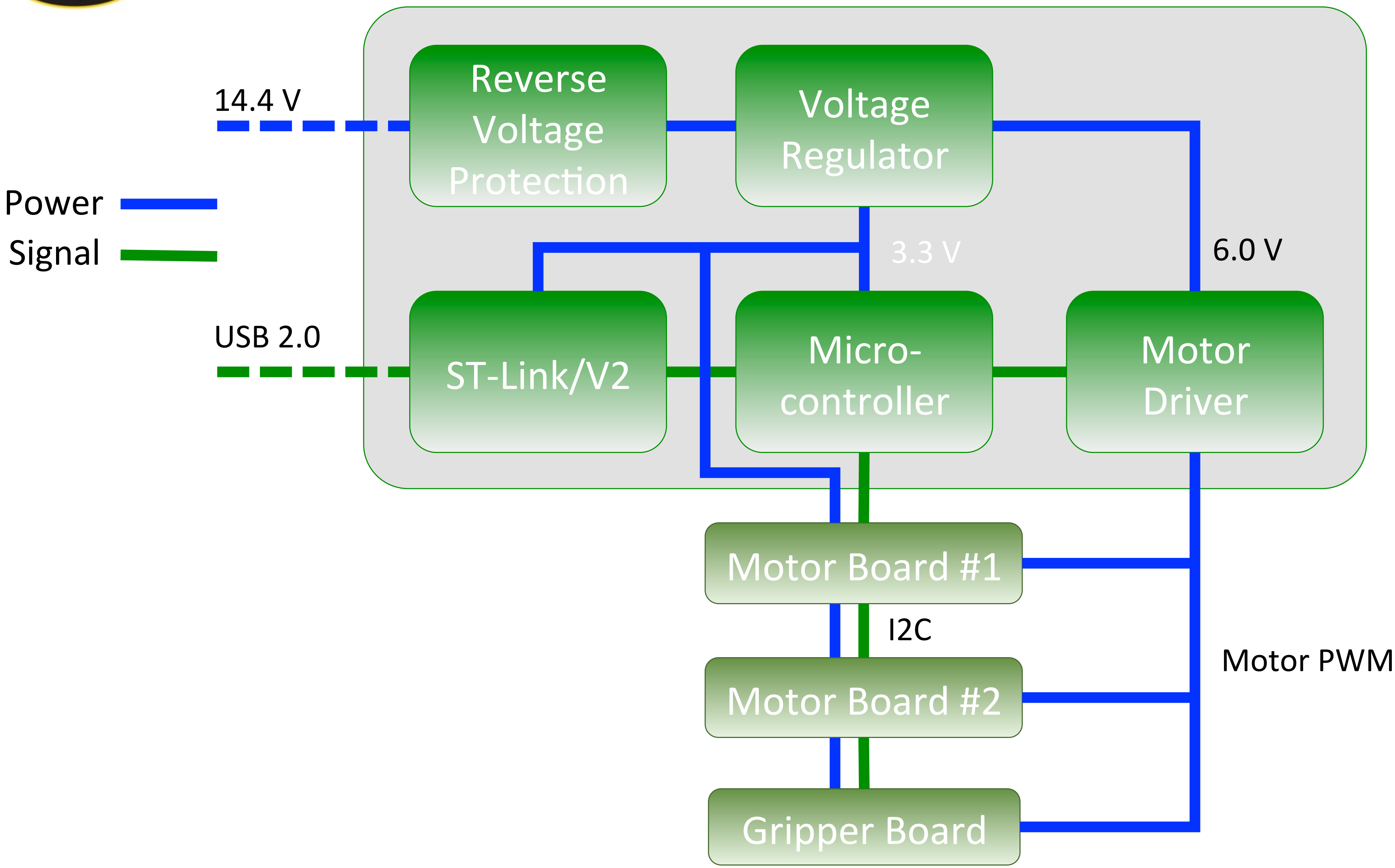
Perch Cam Location



- The minimum distance between perch cam and handrail is 12.5 cm
- CamBoard Pico Flexx provides 6 predefined modes, but activation code is required to change the range/frame rate/exposure time manually

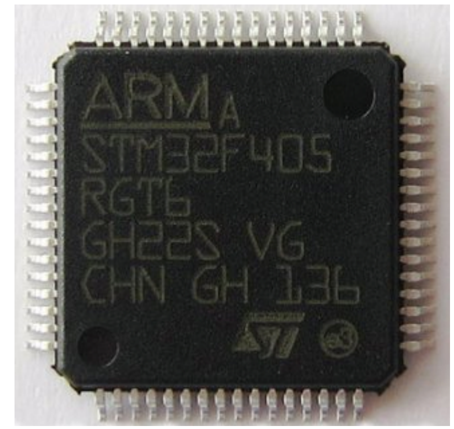
Nr	Use Cases	Operation Modes	Frequencies	Range [m]	Framerate	Int. Time (us)
1	Indoor room reconstruction	MODE_9_5FPS_2000	80 & 60 MHz	1 - 4.0	5 fps	2000
2	Room scanning, indoor navigation	MODE_9_10FPS_1000	80 & 60 MHz	1 - 4.0	10 fps	1000
3	3D object reconstruction	MODE_9_15FPS_700	80 & 60 MHz	0.5 - 1.5	15 fps	700
4	Medium size object Recognition, face reconstruction	MODE_9_25FPS_450	80 & 60 MHz	0.3 - 2.0	25 fps	450
5	Remote collaboration, step by step instruction, table-top gaming	MODE_5_35FPS_600	60 MHz	0.3 - 2.0	35 fps	600
6	Small object/product recognition, Hand tracking	MODE_5_45FPS_500	60 MHz	0.1 - 1.0	35 fps	500

Block Diagram of Controller Board



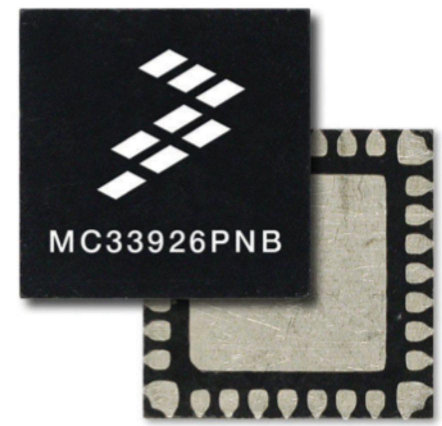
Microcontroller

- STM32F405
  - ARM Cortex-M4 32b MCU+FPU
  - Frequency up to 168 MHz
  - Up to 17 timers
    - 12 x 16-bit timer, 2 x 32-bit timer
  - 6 x QEP module
    - Calculating motor encoder pulse
  - 3 x 12-bit A/D converters
    - Calculating input current to 3 motor drivers



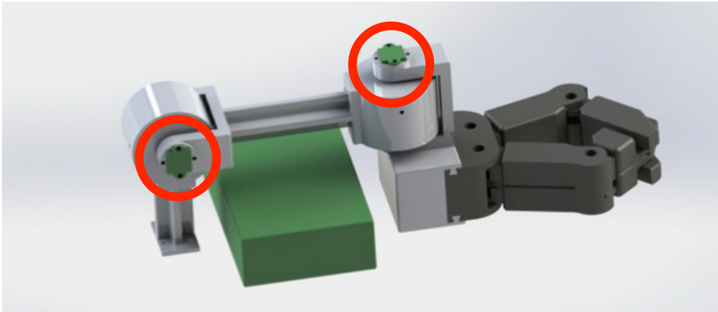
Motor Driver

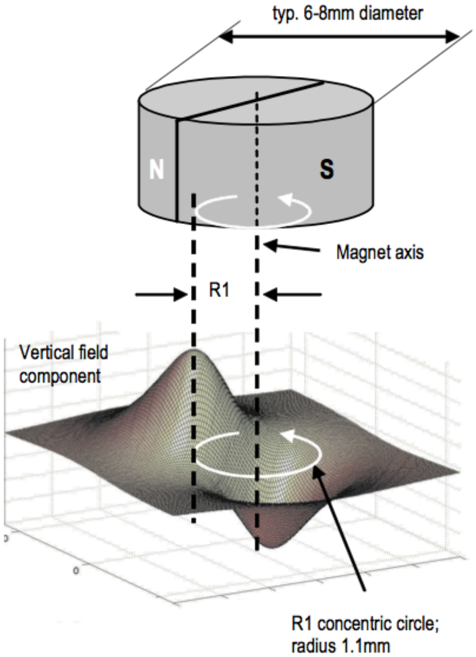
- MC33926
  - 5 V to 28 V continuous operation
  - 3 V/5V TTL/CMOS logic compatible inputs
  - Overcurrent limiting
  - Output short-circuit protection
  - Load current feedback



Magnetic Rotary Encoder

- AS5048
  - Absolute position sensor
  - Contactless rotary position sensor over 360°
  - Measure the absolute position of the magnet's rotation angle with a 14-bit high resolution output (0.05° accuracy)
  - The zero position can be programmed via I²C command

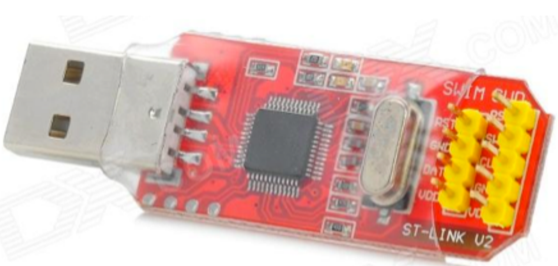


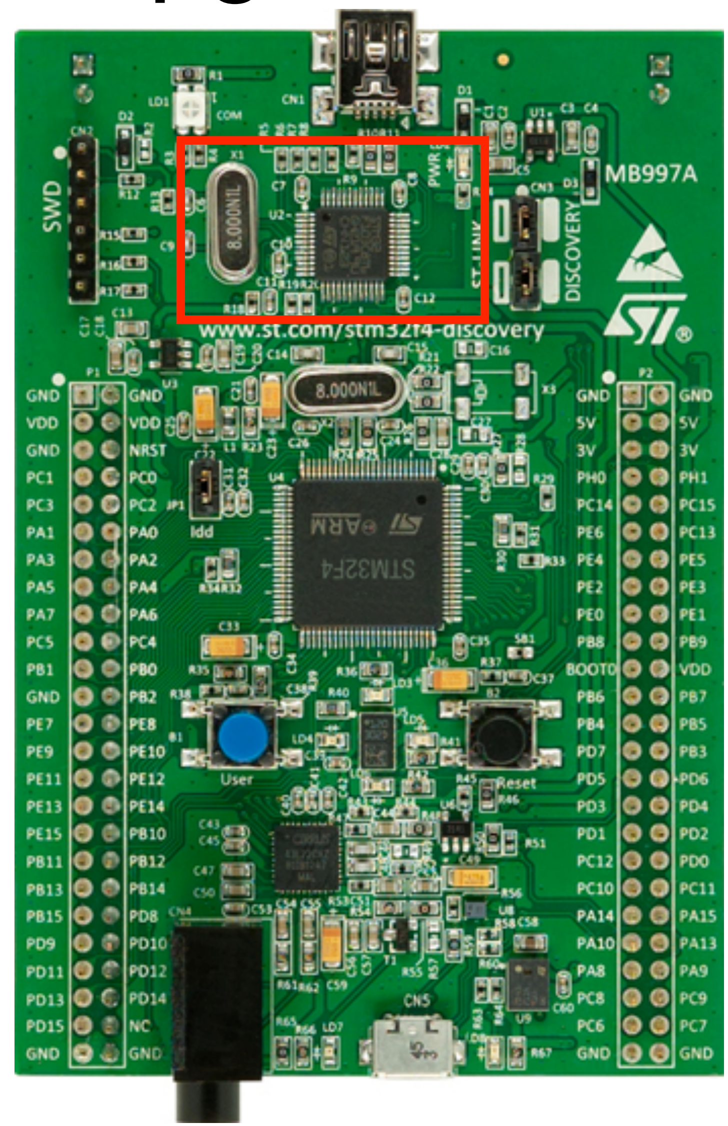


Remote Software Upgrade

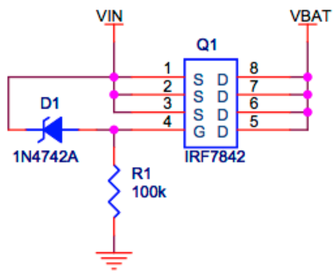
✔ [FFREQ-441] *The Perching Arm shall be capable updating software.*

- Able to compile and upgrade firmware remotely in Linux using STM32F4 discovery board
- Require ST/Link-V2
  - In-circuit debugger and programmer
  - Controller board must include premade ST/Link-V2 board

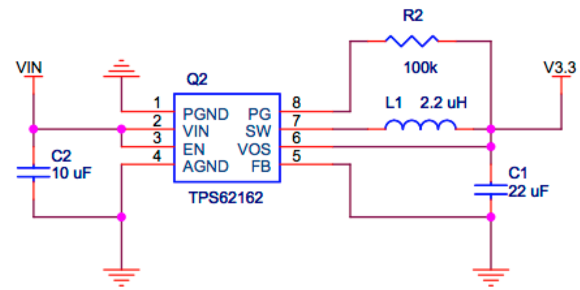




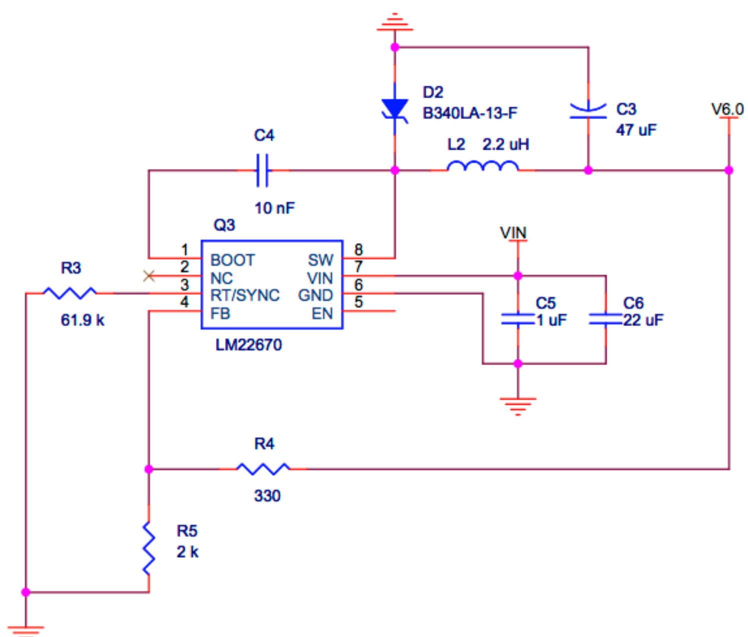
Controller Board Schematics



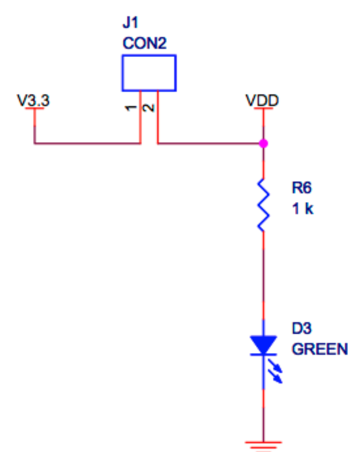
Reverse-voltage Protection



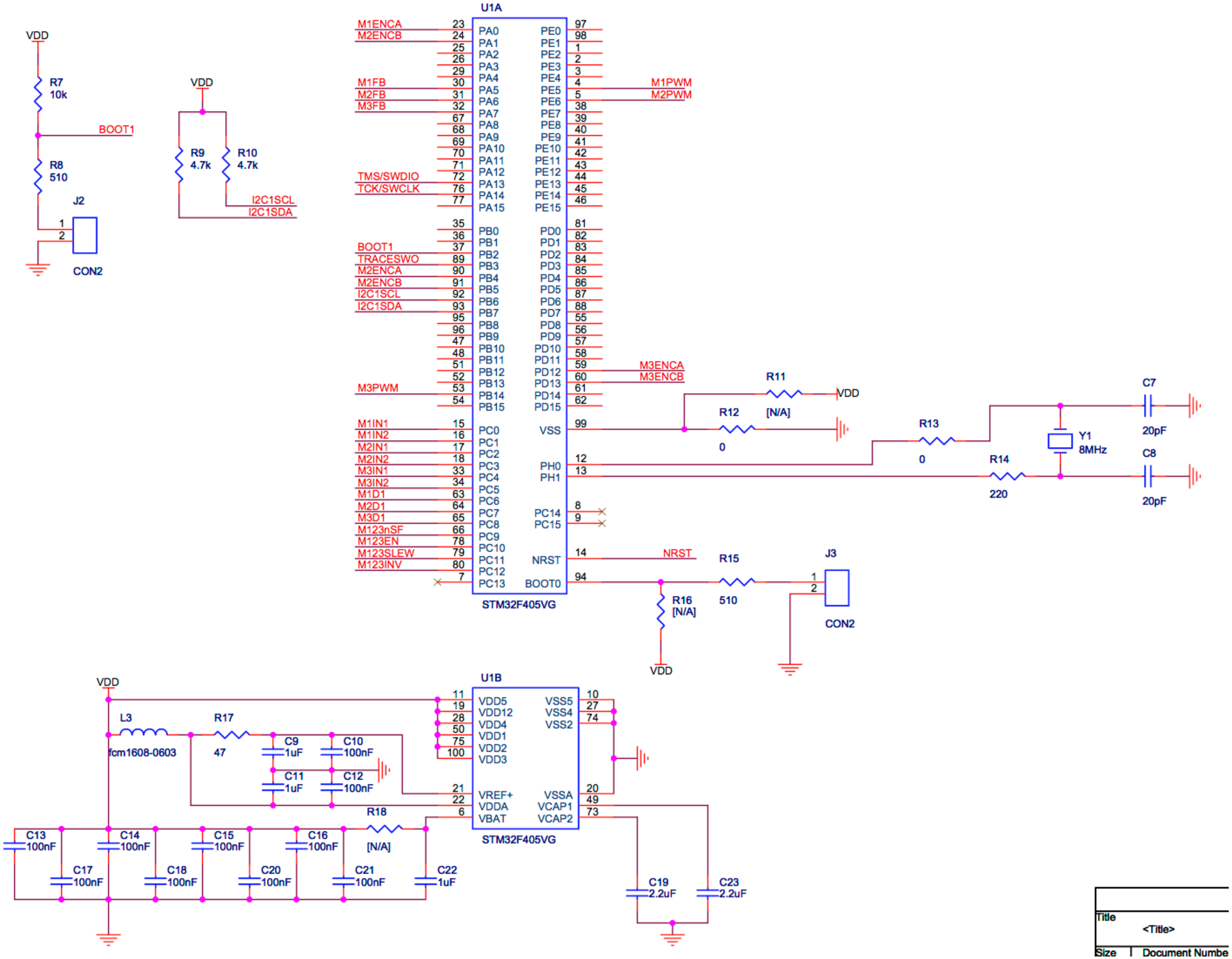
3.3V/1A Voltage Regulator



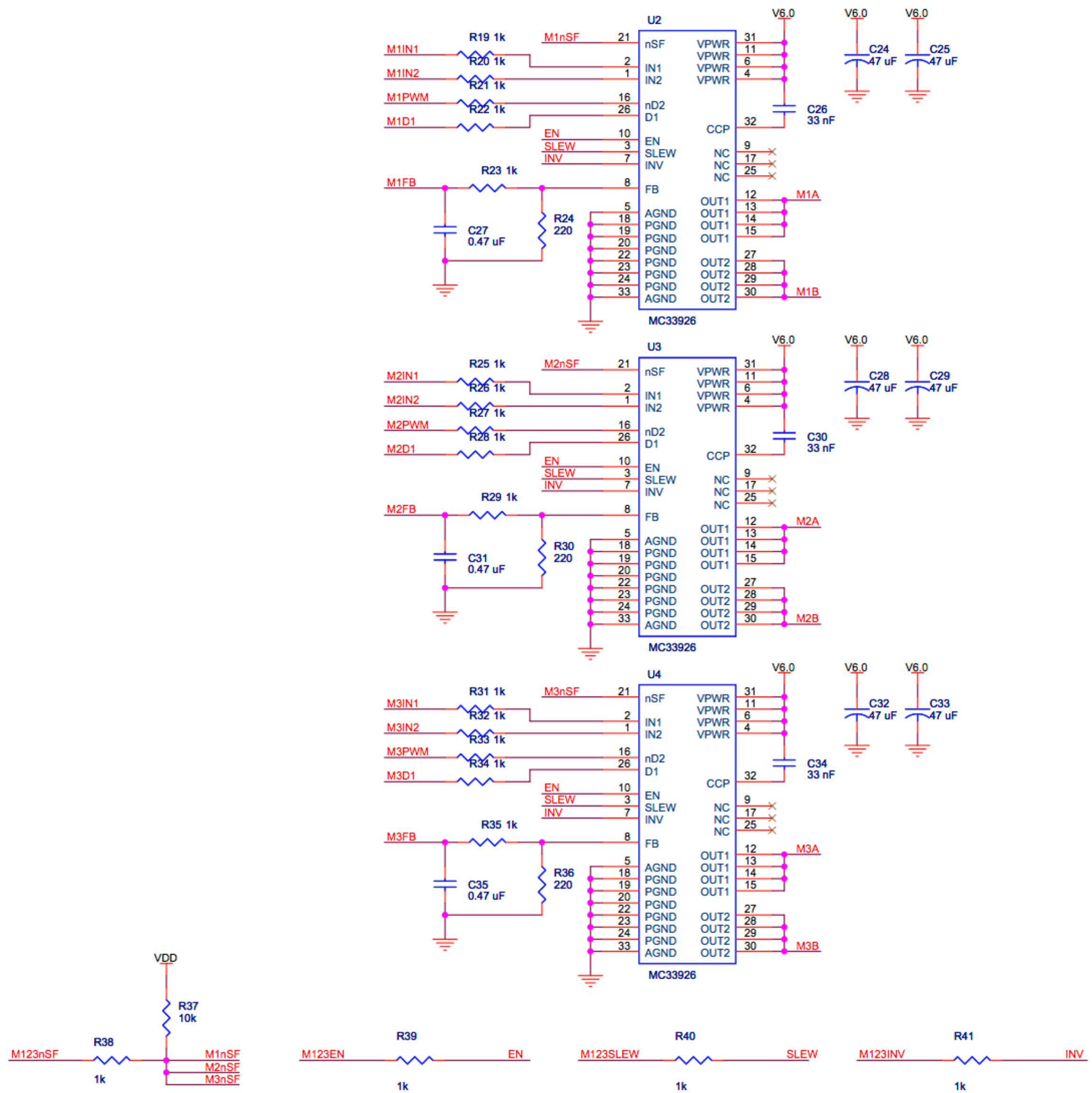
6.0V/3A Voltage Regulator



Controller Board Schematics



Controller Board Schematics



Astrobee Thermal Subsystem

Design Overview

Subsystem Team

- Jeffrey Feller (ARC-RE, alum)

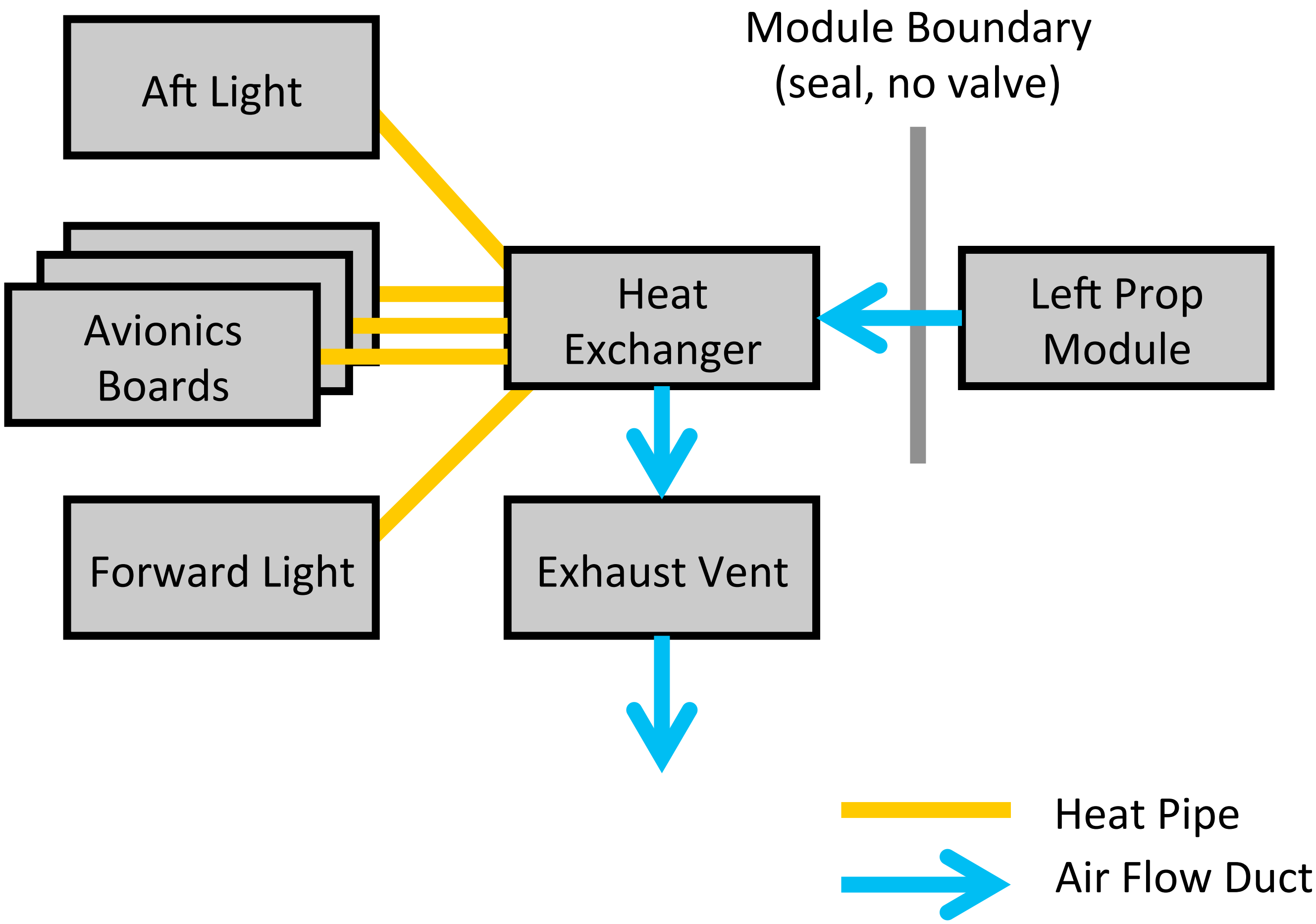
Design Drivers

- Reject heat produced by avionics
- Surface touch temperature limit from ISS human factors
- No gravity driven convection in 0g
- Minimize thermal subsystem power draw and impact on GN&C

Trade Study

- External radiator would not suffice to reject max power from avionics box
- Proposed solution uses a heat exchanger

Architecture Diagram



Pros and Cons

- Pros
  - Heat flow predictable; should behave very similarly between ground testing and 0g
  - Heat pipes and heat exchanger produce high heat flow with low mass and volume
  - Bleeding air off prop module eliminates dedicated thermal fan
  - No dedicated thermal moving parts in operation
- Cons
  - Must spin large blower to produce air flow (can't idle blowers for extended periods when processors running)
  - Thermal air flow overhead reduces max thrust and power efficiency of propulsion module
  - Need low-pressure seal at module boundary

Astrobee Dock Mechanical Subsystem

Design Overview

Subsystem Team

- Rafael “Omar” Talavera (ARC-RE, Lead)
- Travis Mendoza (ARC-RE, Intern)
- Hugo Sanchez (ARC-RE)

Design Drivers

- Two Free Flyer berths
- Battery charging
- Autonomous docking
  - 5deg angular error
  - 1cm position error
- Human Factors
  - Kick loads while docked
  - Connector pin protection
- Location within ISS
  - Determined by Topology Group
  - Will constrain volume and keep-out zones

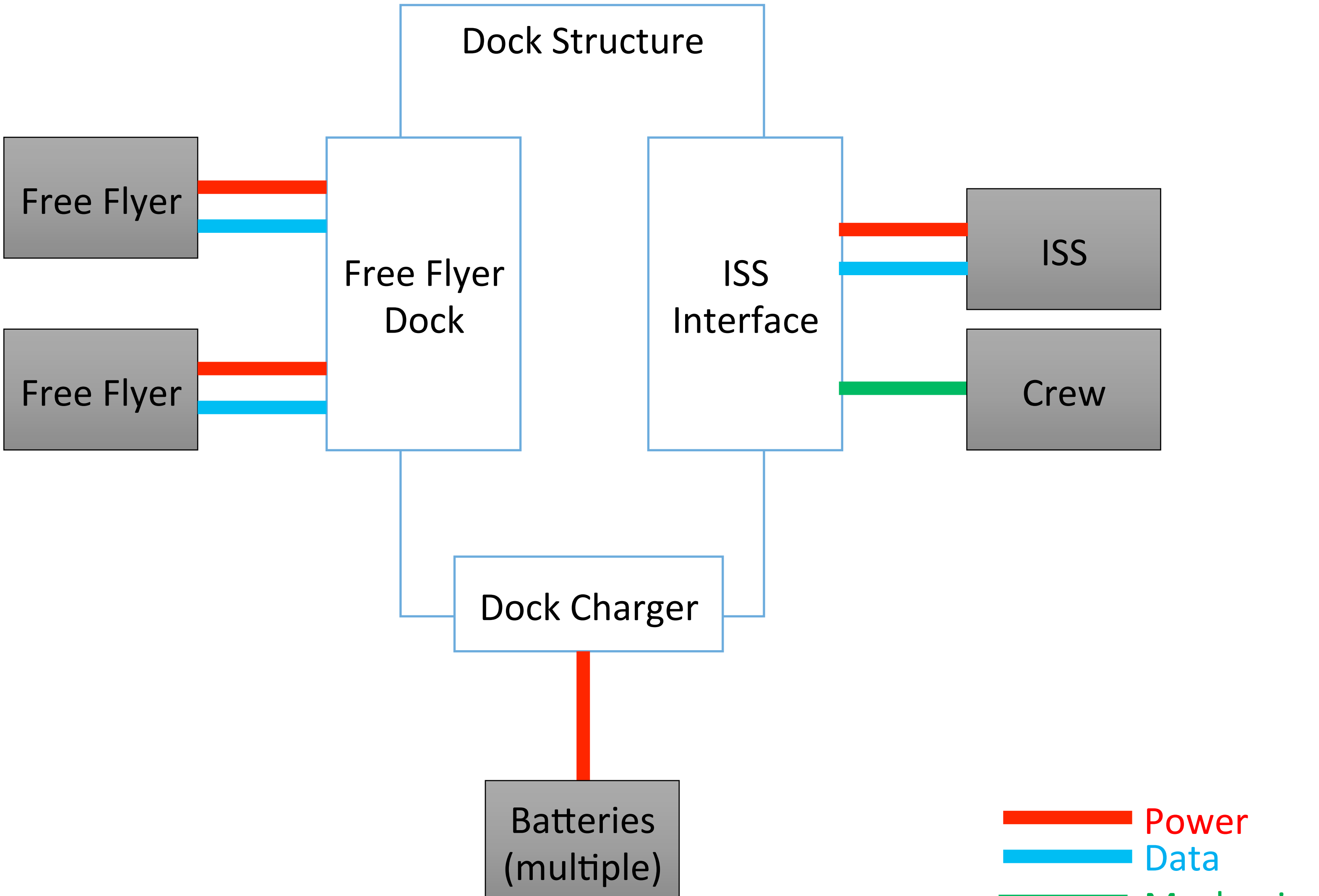
Trade Study

Attributes	Options
Lance	• Cone • Cone and cylinder • Cone, cylinder, and head
Retention System	• Magnet and linear actuator • Electromagnet
ISS Mounting	• Single Seat track • Double Seat Track • Velcro

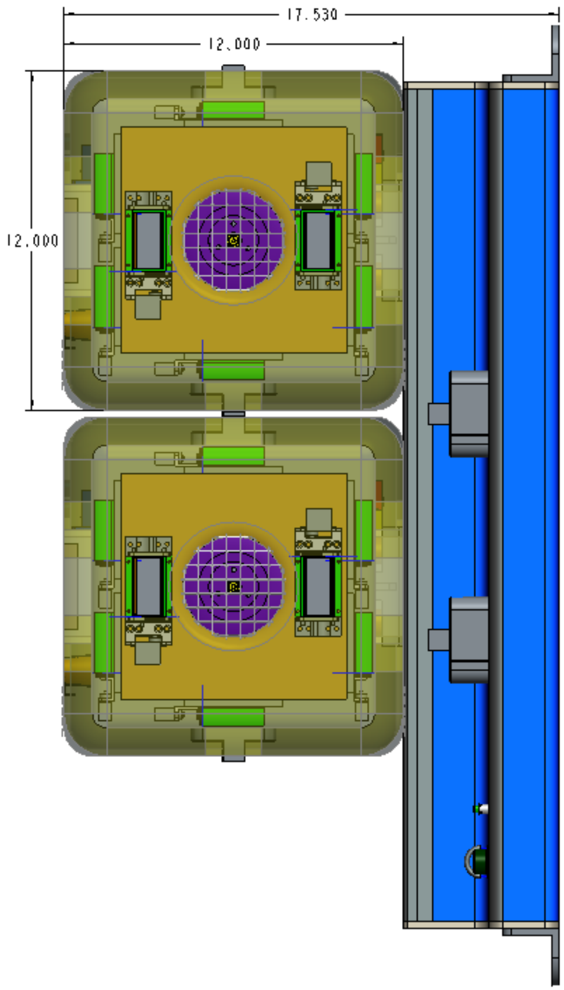
Selected Design

- **Cone shaped lance**
  - Pros
    - Easy detachment in case of lateral kick load
  - Cons
    - Less precise position near final engagement
- **Single seat track**
  - Pros
    - Preliminary approval from ISS topology group
    - Secure mounting
  - Cons
    - Limited mounting options on ISS
    - Width may be constrained by rack payloads

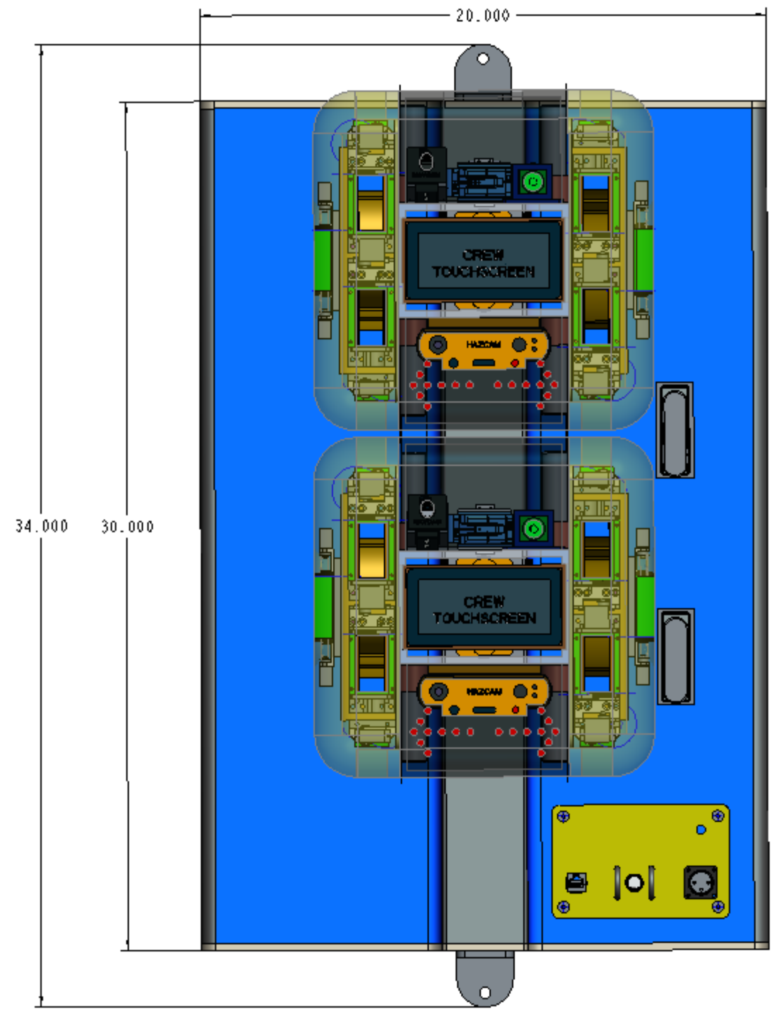
Architecture Diagram



Drawing

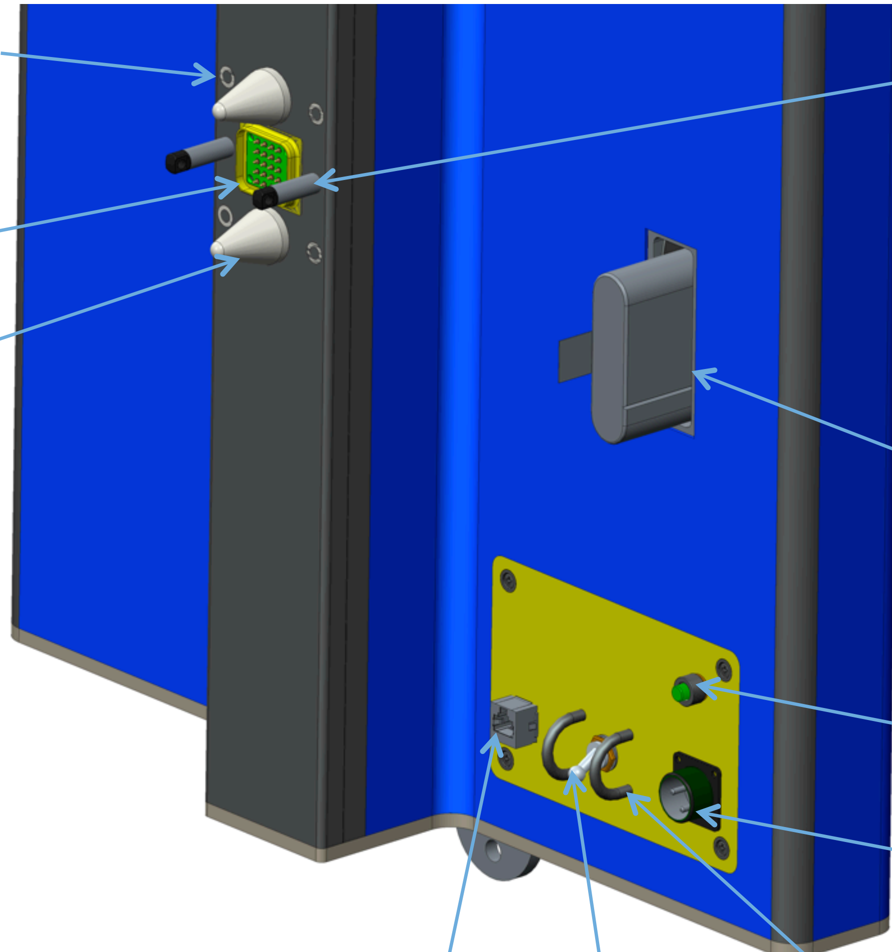


Side view



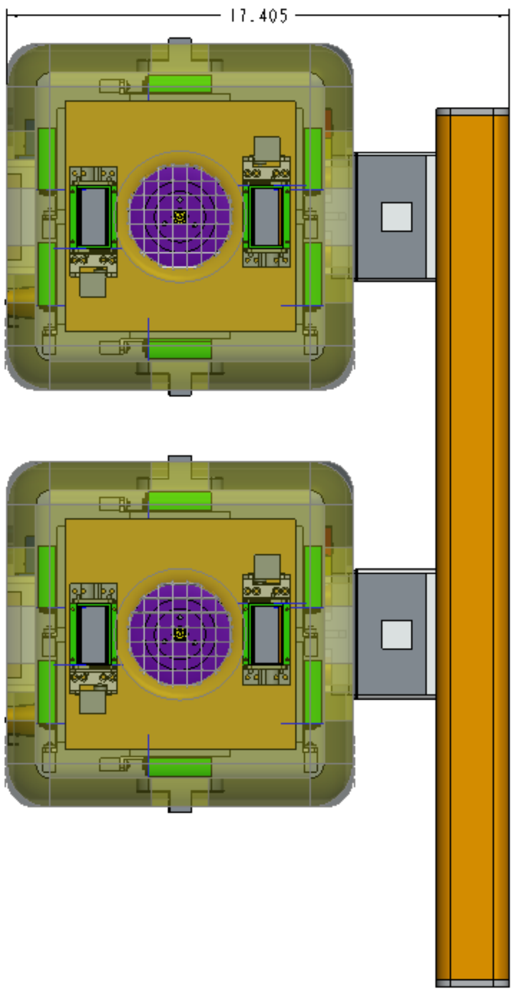
Front view

Option 1 Drawing

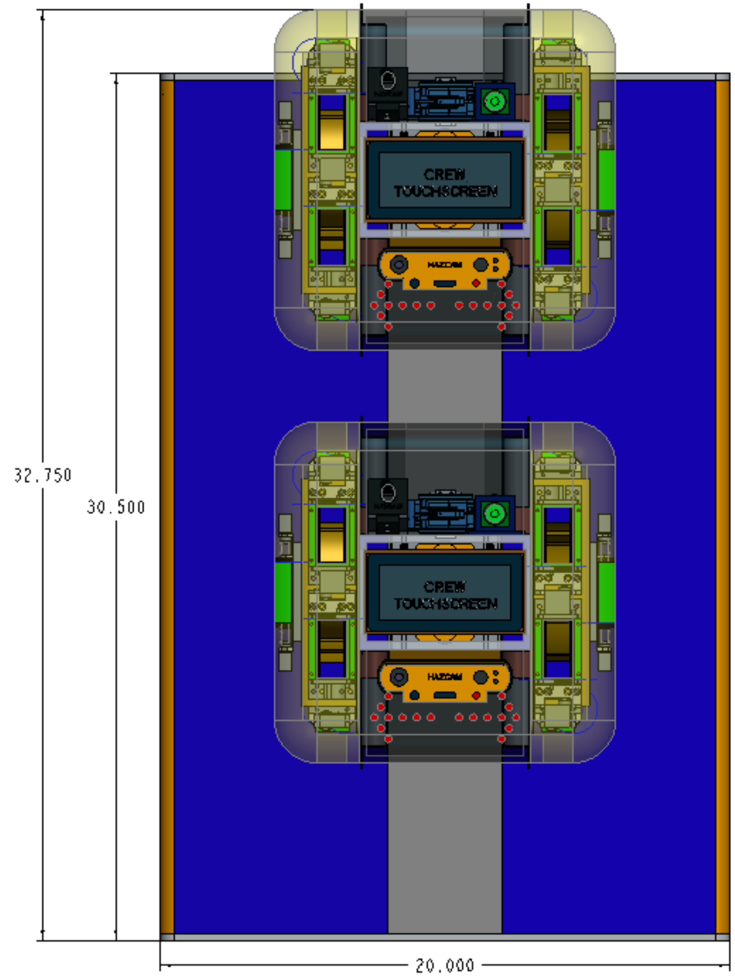


Detail view

Option 2 Drawing

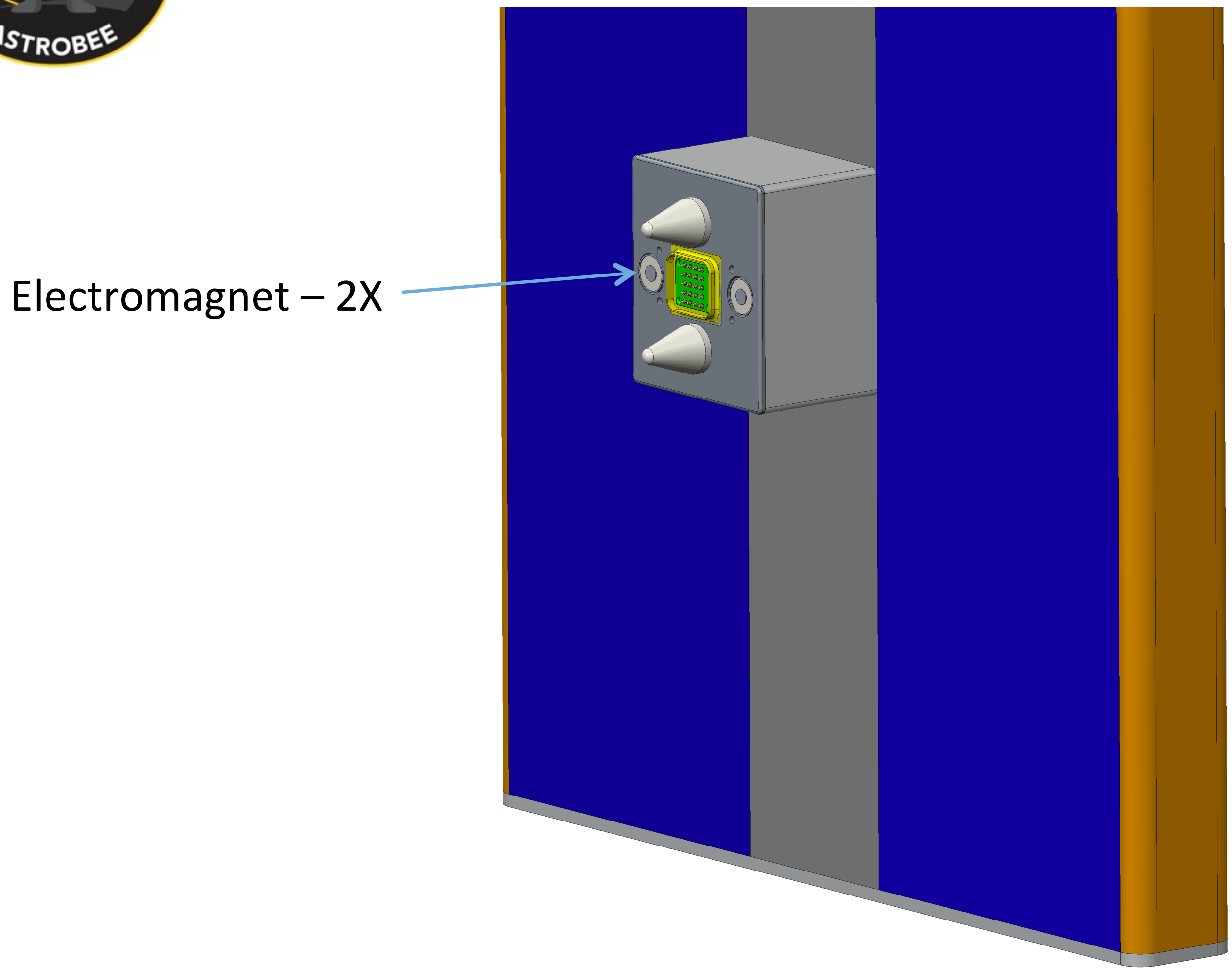


Side view



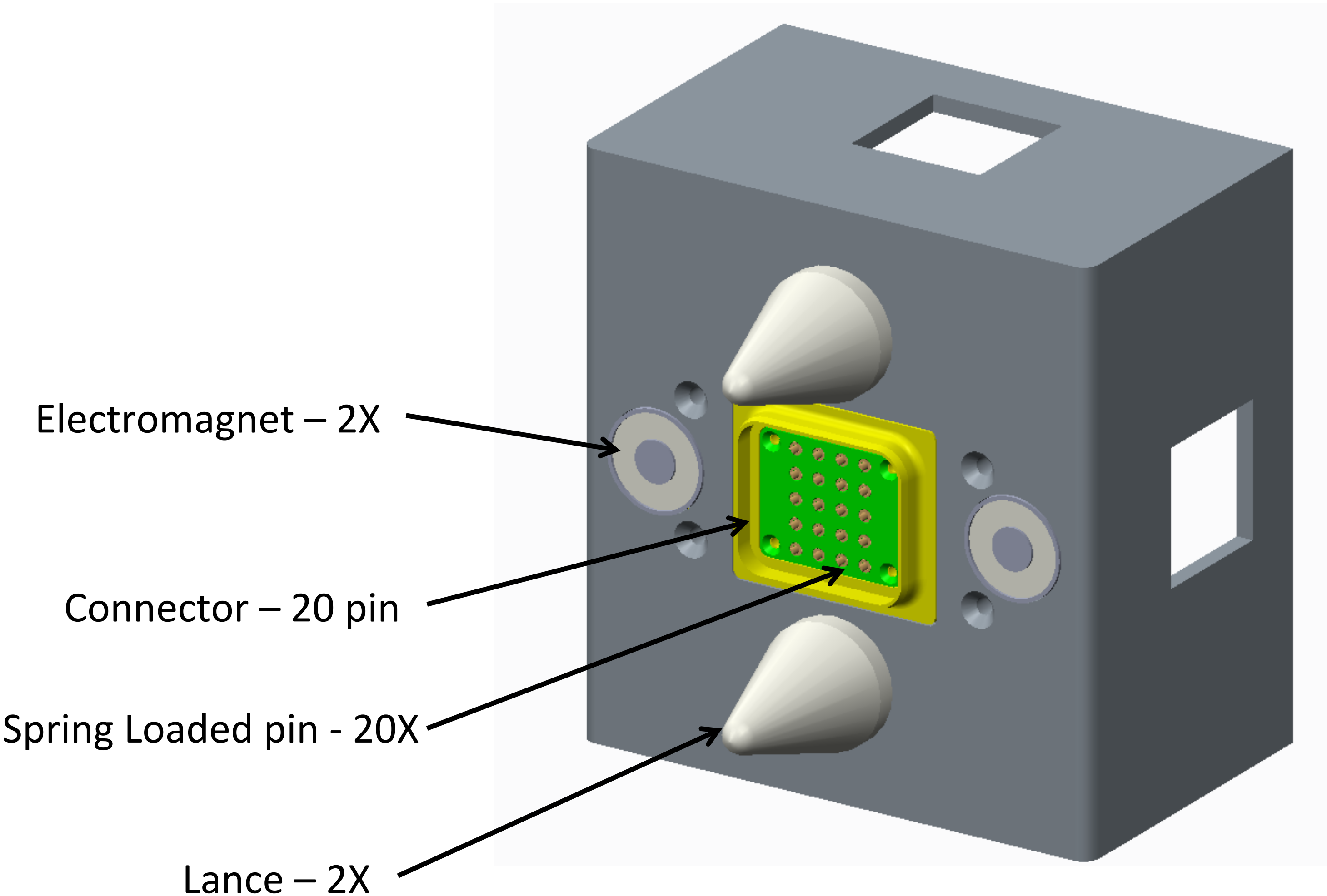
Front view

Option 2 Drawing

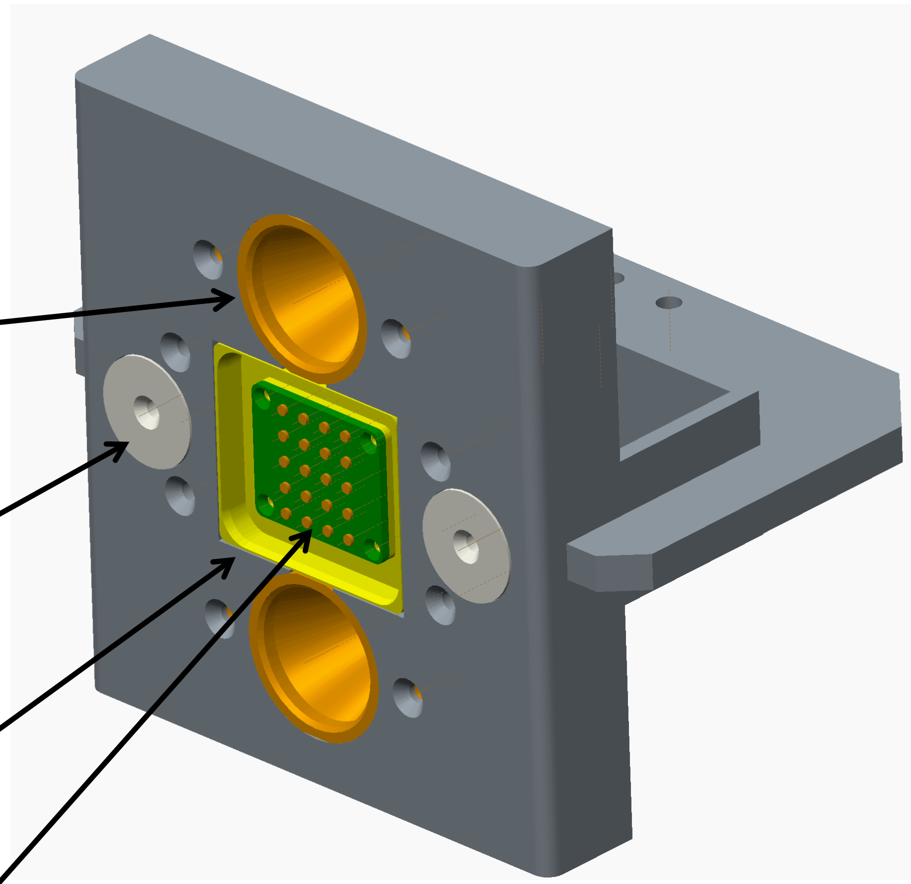


Detail view

Dock Interface

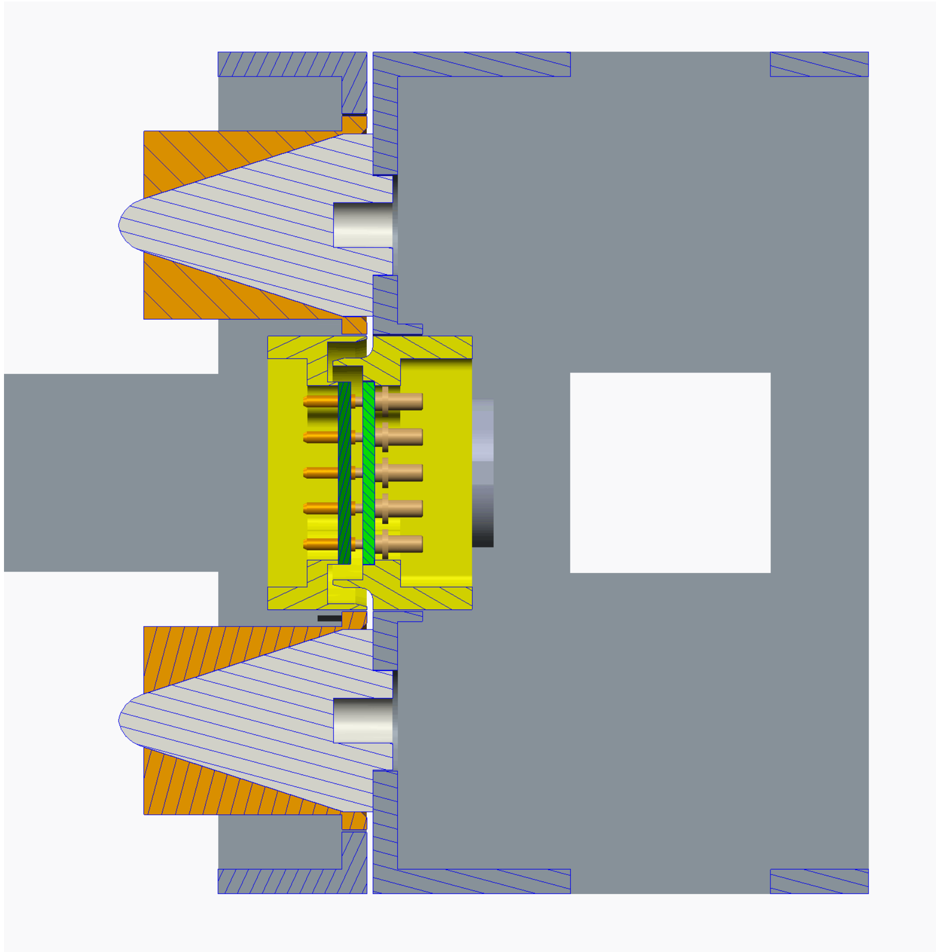


Astrobee Interface



X-Section
Full Dock

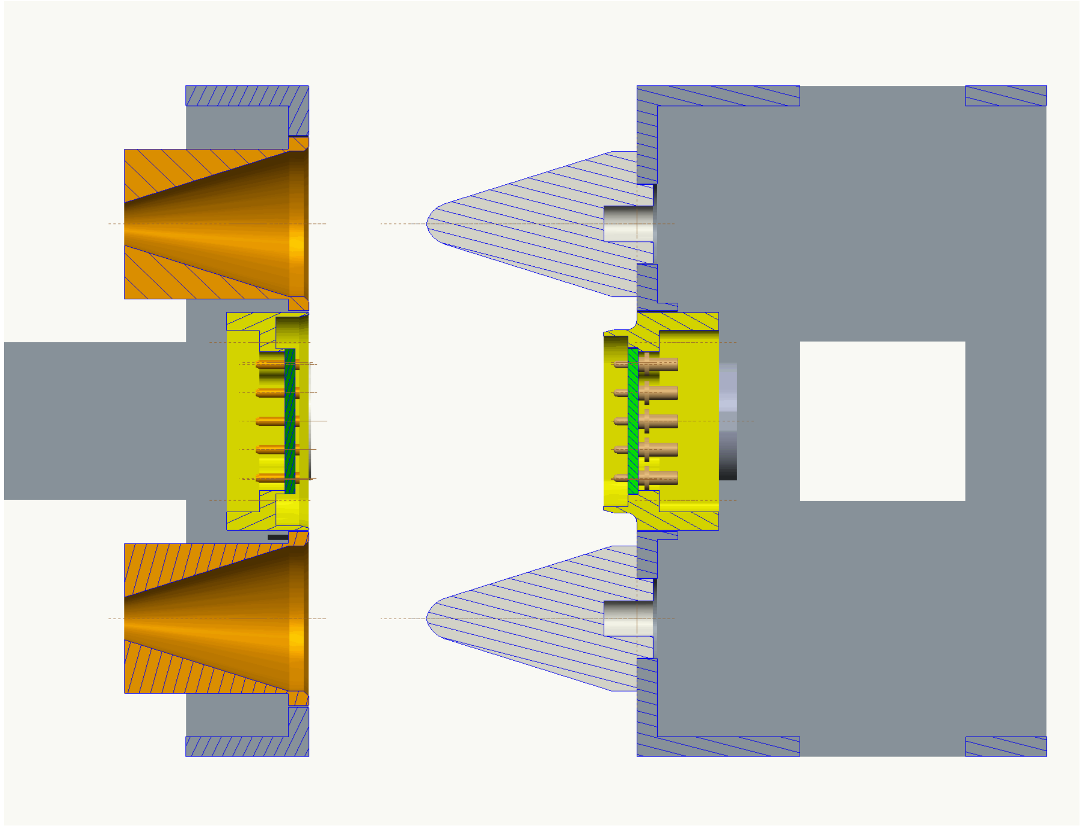
Flyer Side



Dock Side

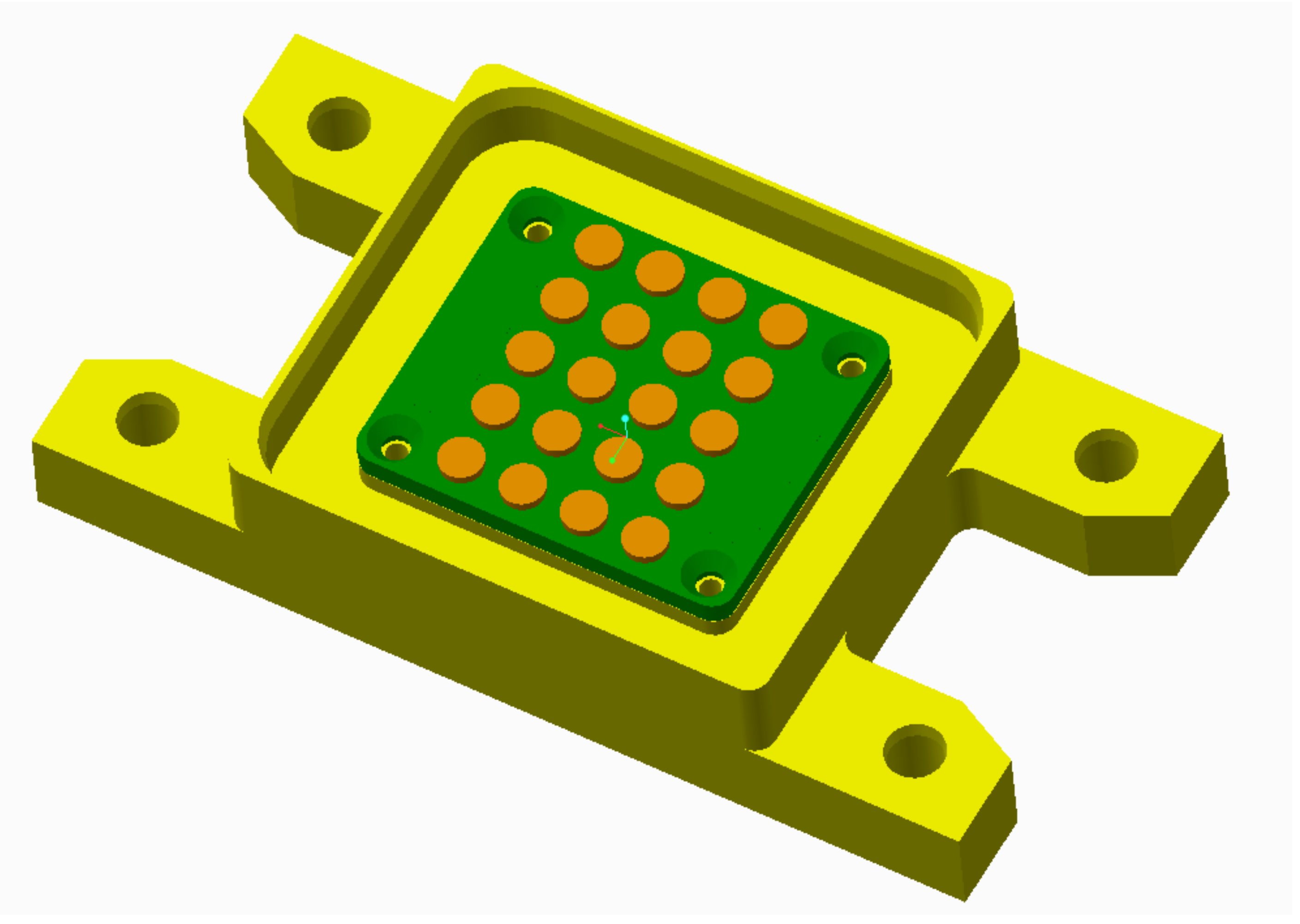
X-Section Cont.

Astrobee Side

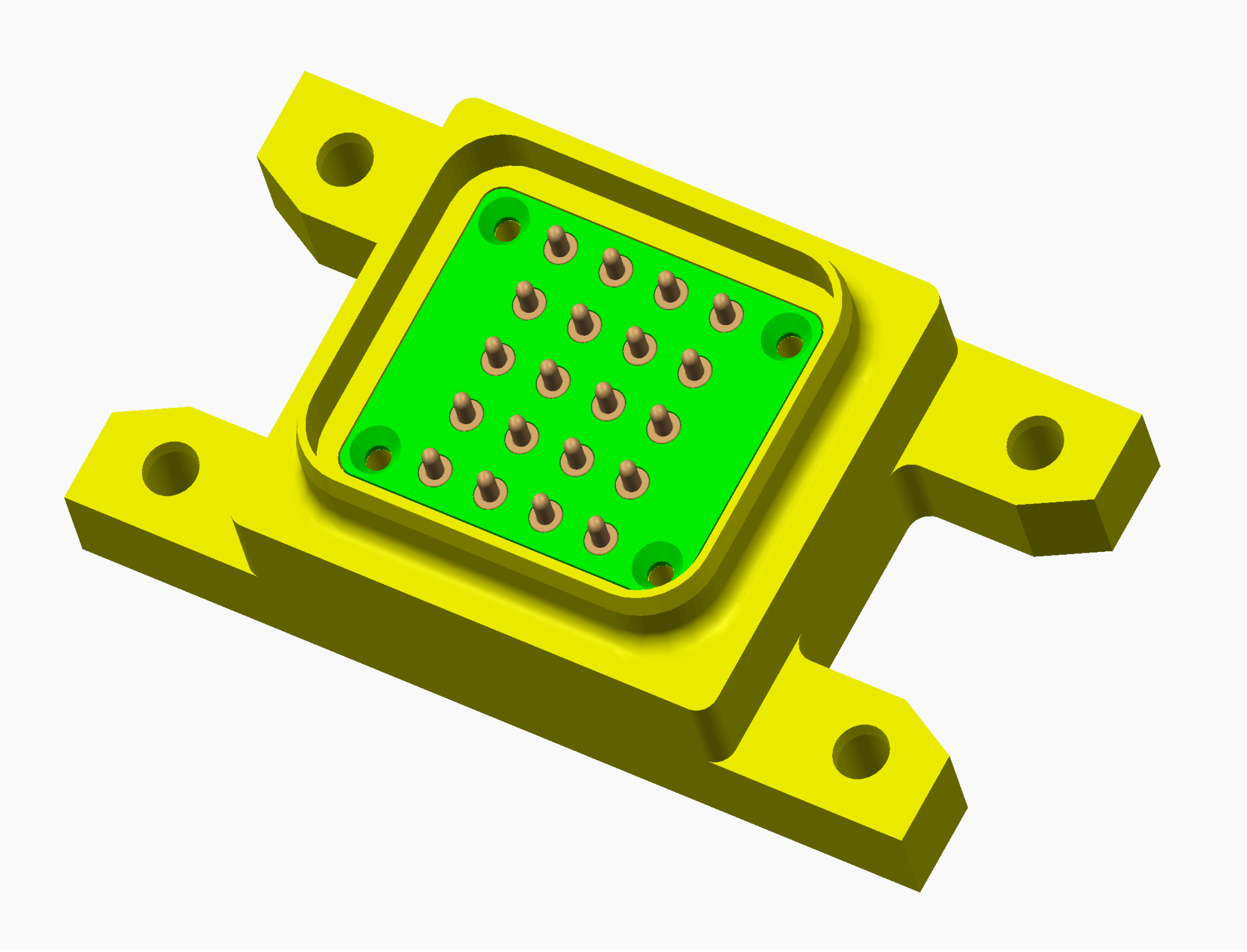


Dock Side

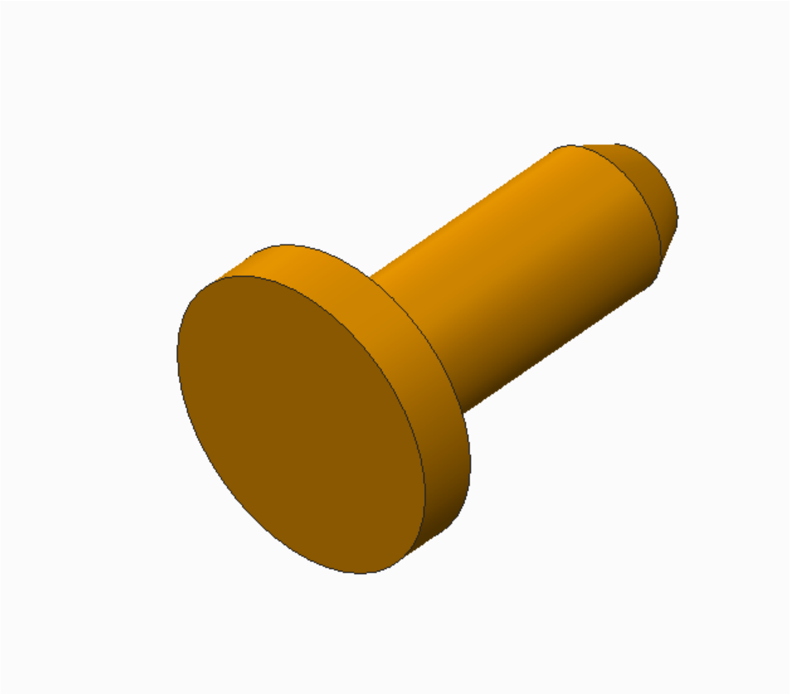
20 Pin Connector - Flyer



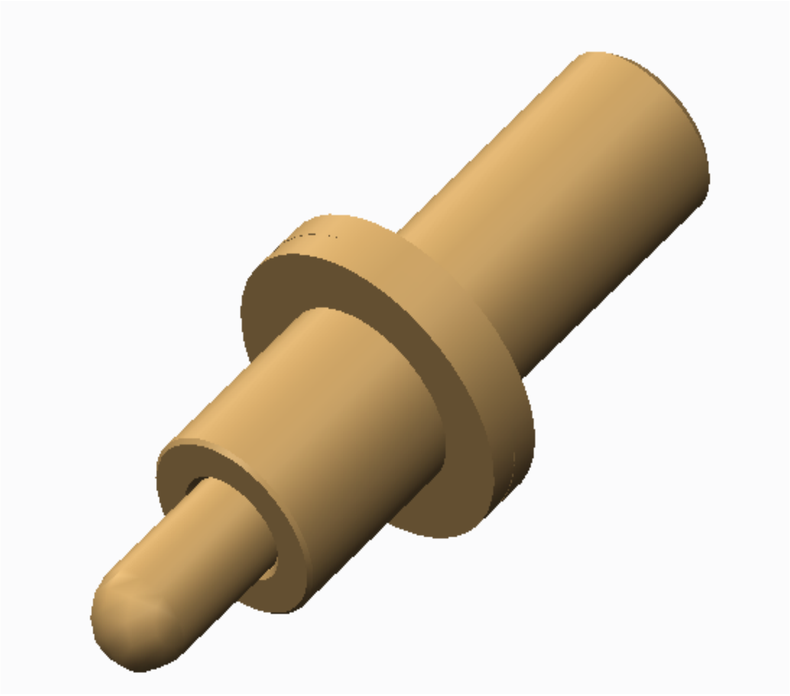
20 Pin Connector - Dock



Mill Max Connectors

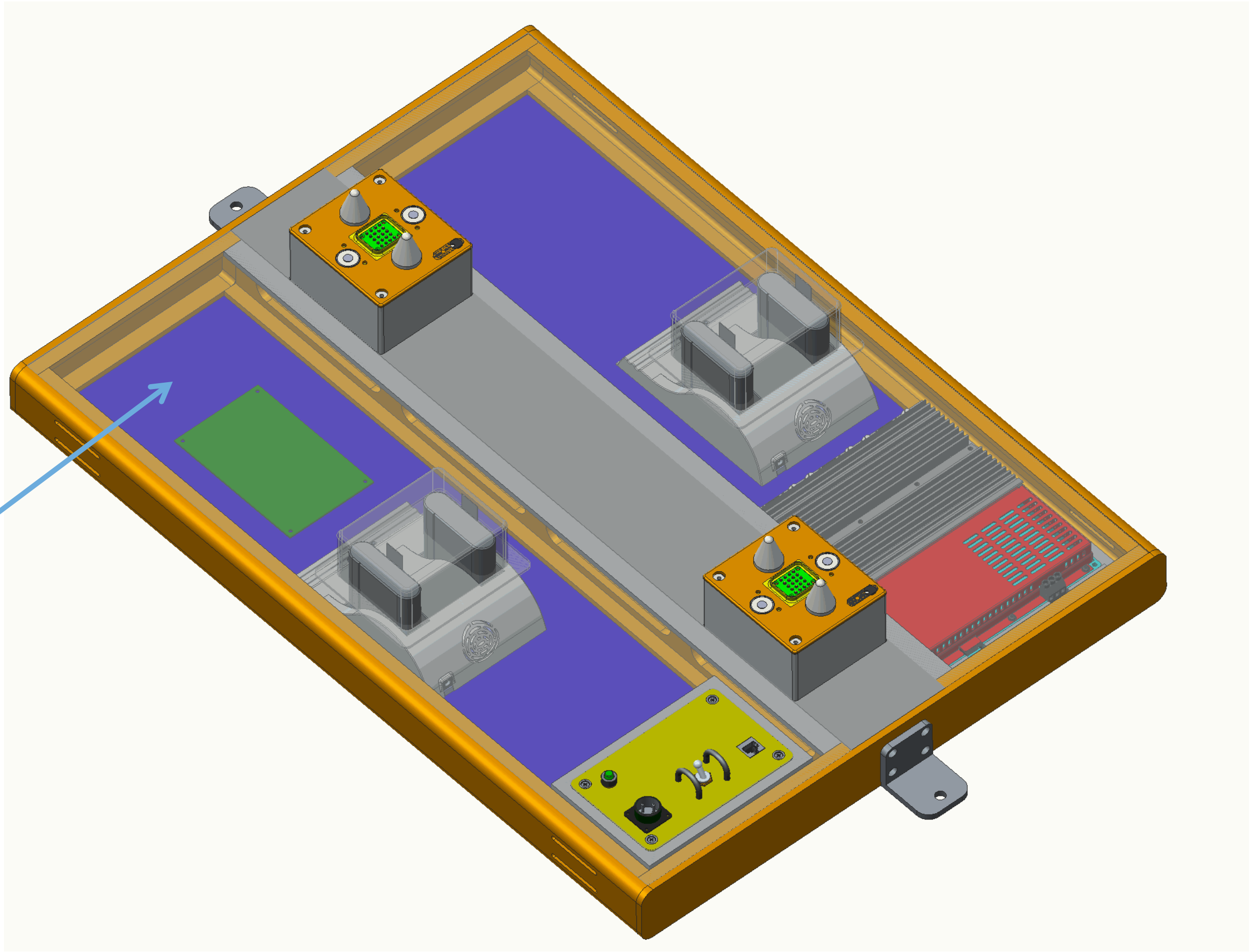


Nail Head Pin - Flyer Connector



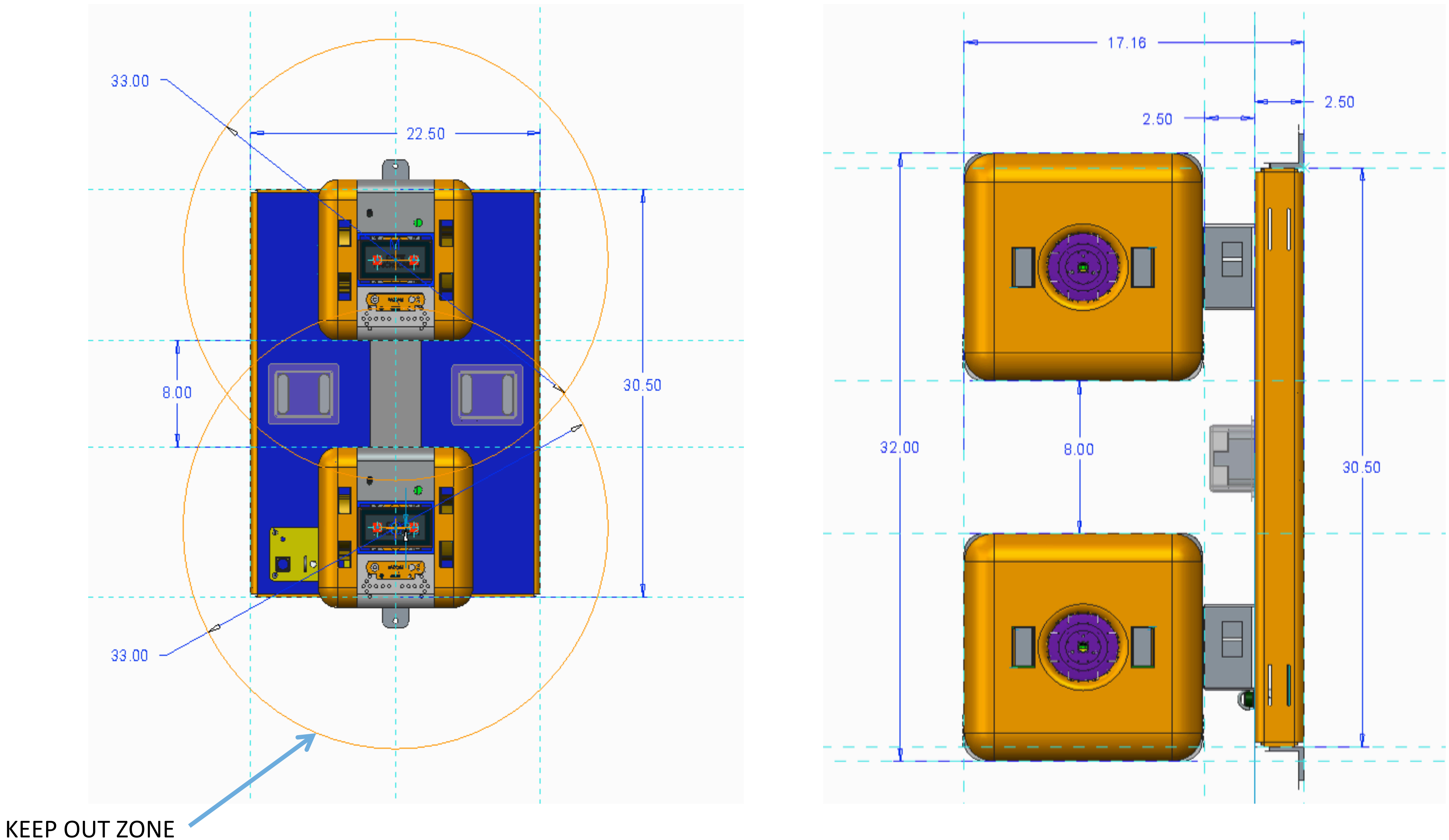
Spring Loaded Pin - Dock Connector

ISO View - Dock

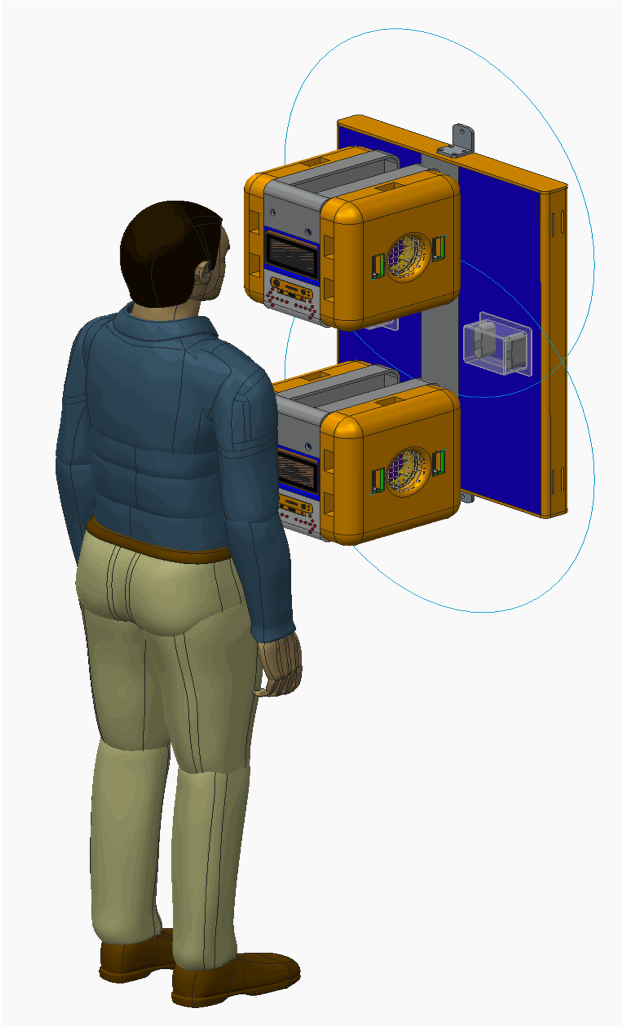


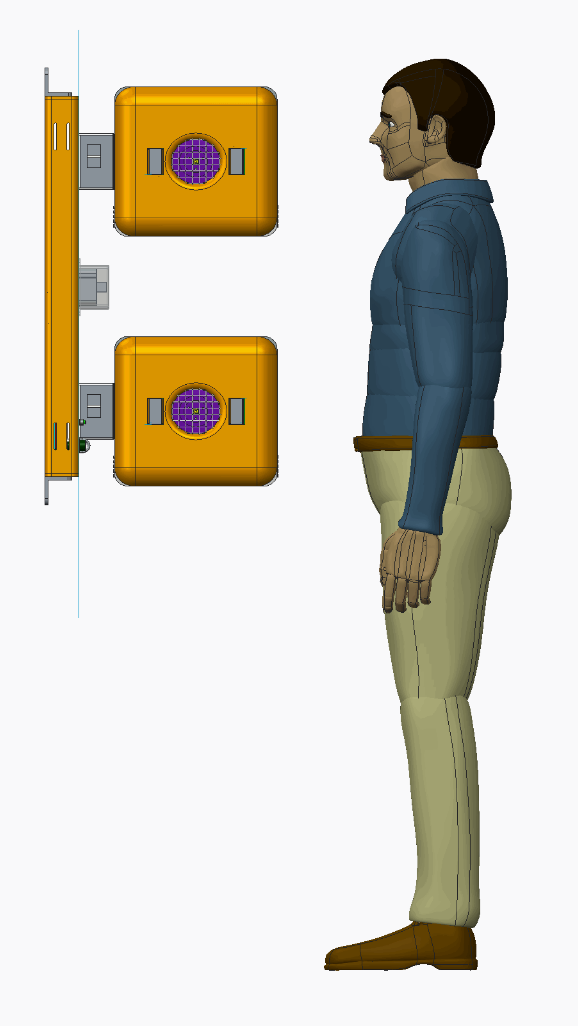
COVERS SHOWN
TRANSPARENT
FOR CLARITY

Flyer and Dock
Front and Side View

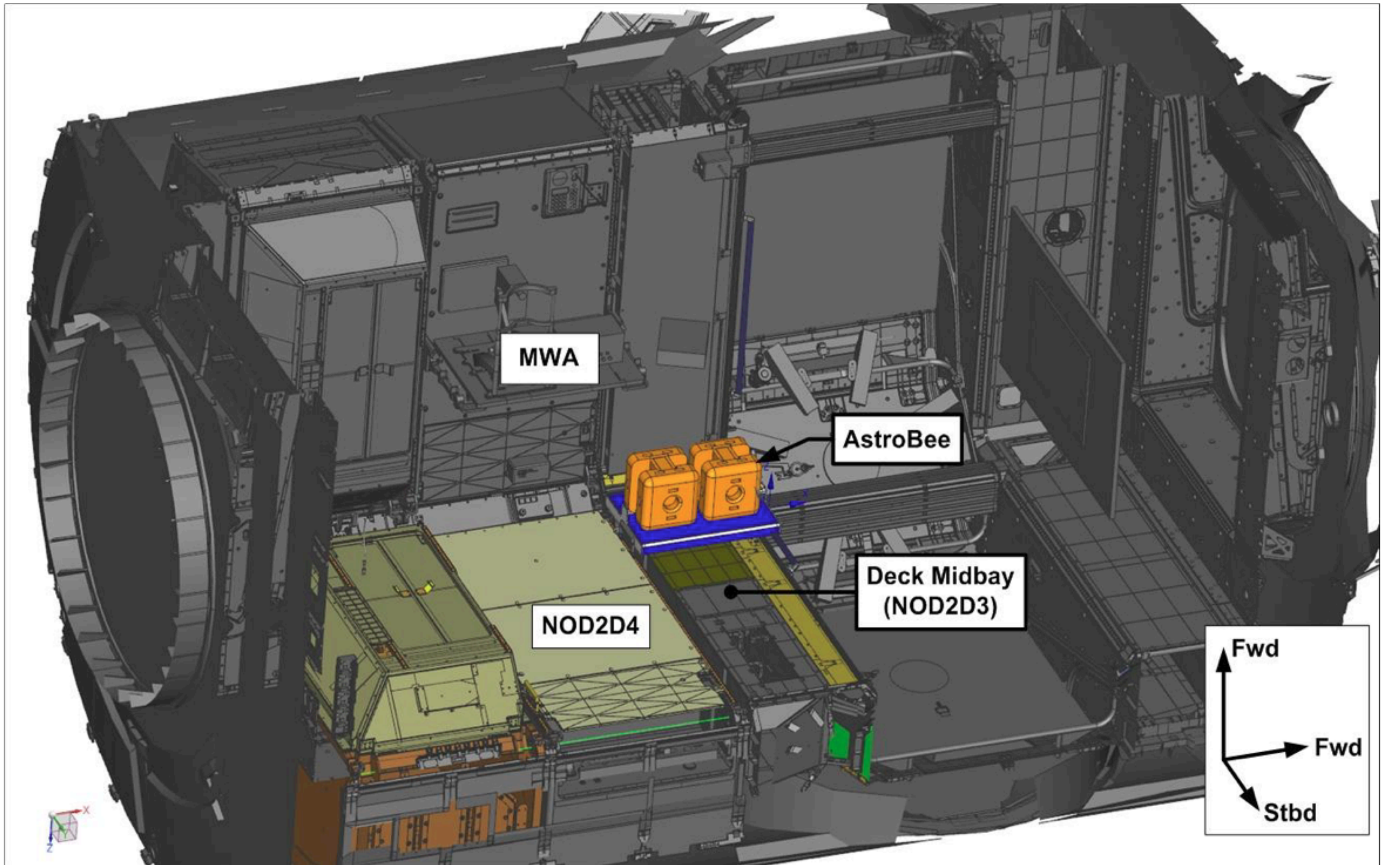


Flyer and Dock





Dock Placement Study



Component List

Component	Quantity	Source	Part No.
Light Indicator LED	1	Dialight	50739181472600F
Light Indicator Socket	1	Dialight	5088738504
On/Off Switch	1	Sensata/Klixon	7270-1-20
Switch Guard	2	Perihelion Design	PDM-012
RJ45 Connector	1	Switchcraft Inc.	EHRJ45P6S
AC/DC Converter	4 (in 1 package)	Vicor	VI-RU0YI-IWXY-CC
Power Connector	1	TBD	TBD
Battery	2	Inspired Energy	ND2054HD34
Battery Charger	2	Inspired Energy	CH5000
20 Pin PCB	1	NASA	TBD
Lance	2	NASA	TBD
Retention System Housing	2	NASA	TBD
PCB Connector Housing	1	NASA	TBD
[redacted]			
Countersunk Magnet	4	KJ Magnetics	R622CS-P
Linear Actuator	2	Firgelli Technologies	L12-1
[redacted]			
Electromagnets	2	APW Company	EM075-24-212
Striker Plate	2	APW Company	SP-100

Astrobee Dock Avionics Subsystem

Design Overview

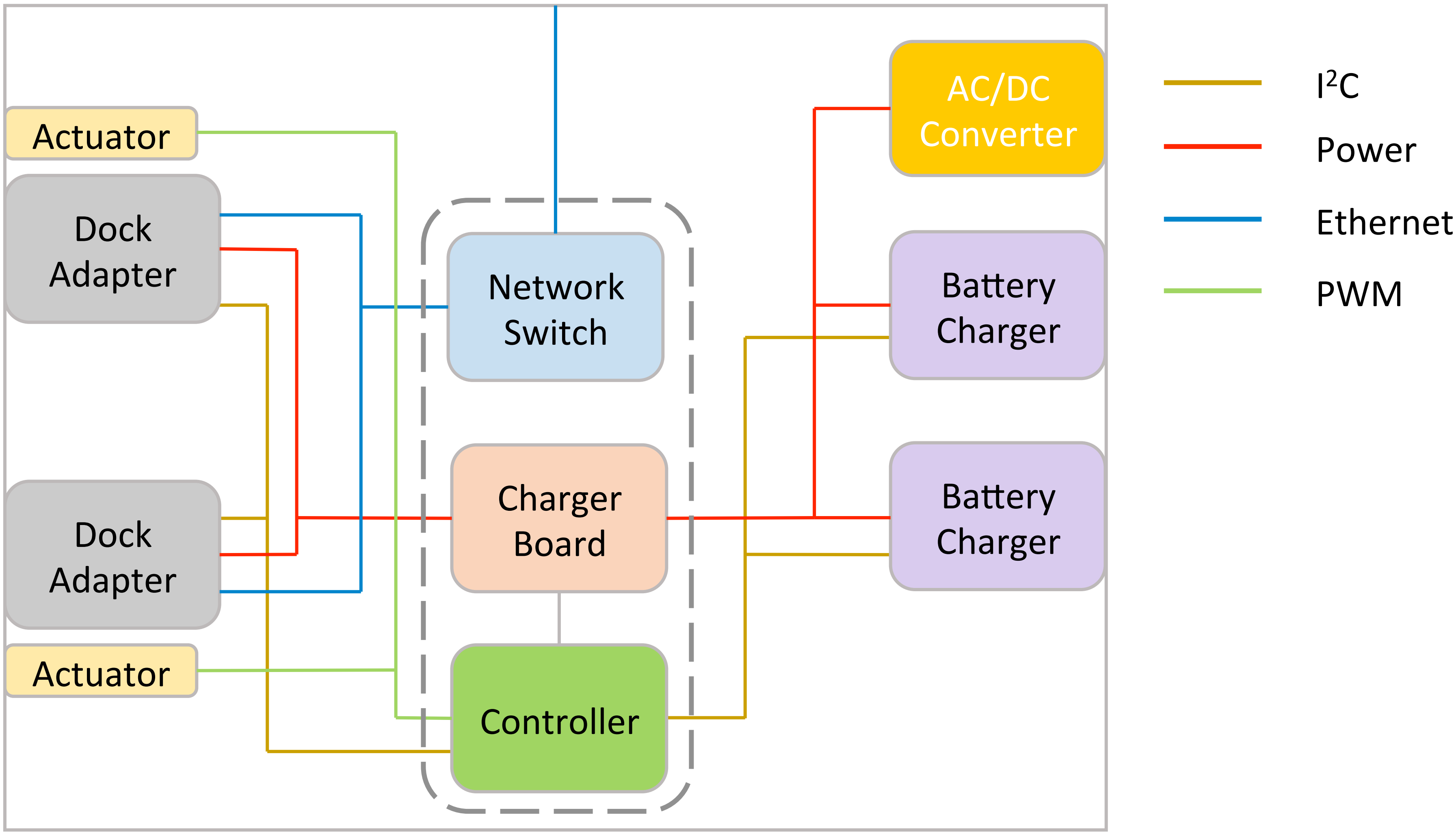
Subsystem Team

- Dmitriy Arbitman (ARC-RE)
- Steve Battazzo (ARC-RE)
- Jon Dewald (ARC-RE)
- Brandon Gigous (ARC-TI, Intern)
- Jason Lum (ARC-TI)
- Nghia Mai (ARC-RE)
- In Won Park (ARC-TI)
- Jongwoon Yoo (ARC-TI)
- Shang Wu (ARC-RE)
- Vinh To (ARC-TI)

Design Drivers

- Provide power to Astrobee
- Provide wired network
- Power and network without crew interaction
- Charge additional batteries
- Modular

Architecture Diagram



Functions

- Provide power to:
  - 2 Docking Astrobee
  - 2 battery chargers
  - Actuator for docking release
- Protection
  - Thermal
  - Power

Component List

- Vicor AC/DC converters (3 output channels)
  - 235mm x 188mm x 35mm
  - Power battery charger
  - Charge 2 Astrobees at 9V @ 3A each
- Network switch to connect Astrobee to wired LAN
- Mating Dock connector to Astrobee would have contacts for Ethernet and power
- Charger board
- COTS battery chargers

Components – Battery Charger

- Using COTS charger from Inspired Energy
  - Provides battery calibration and error resetting
- 2.25”x7”x5”, 360 g
- 24V, 2.5A input
- 3.5 hour recharge time for 49 Wh battery

Connectors

- Pogo pins for network signal & power
- 1,000,000 cycles
- Pin rated for 100V @ 9 A
- 20 pin configuration
- Mounted to PCB

Astrobee GDS Subsystems

Design Overview

Subsystem Team

- DW Wheeler (ARC-TI, Lead)
- Jay Torres (JPL-397G)
- Ryan Goetz (JPL-397J)
- Maria Bualat (ARC-TI)
- Andy Martinez (ARC-TI, Intern)
- Connor Hitt (ARC-TI, Intern)
- Jessica Marquez (ARC-TH) - collaborator
- Youngwoo Park - alumnus
- Hyunjung Kim - alumna

Design Drivers

- Leverage previous GDS "Workbenches" used to control Smart SPHERES and Surface Telerobotics
  - Eclipse RCP
  - RAPID comm protocol
- UI must be simple to learn and use
- UI must comply with IDAGS
- Try not to restrict future functionality

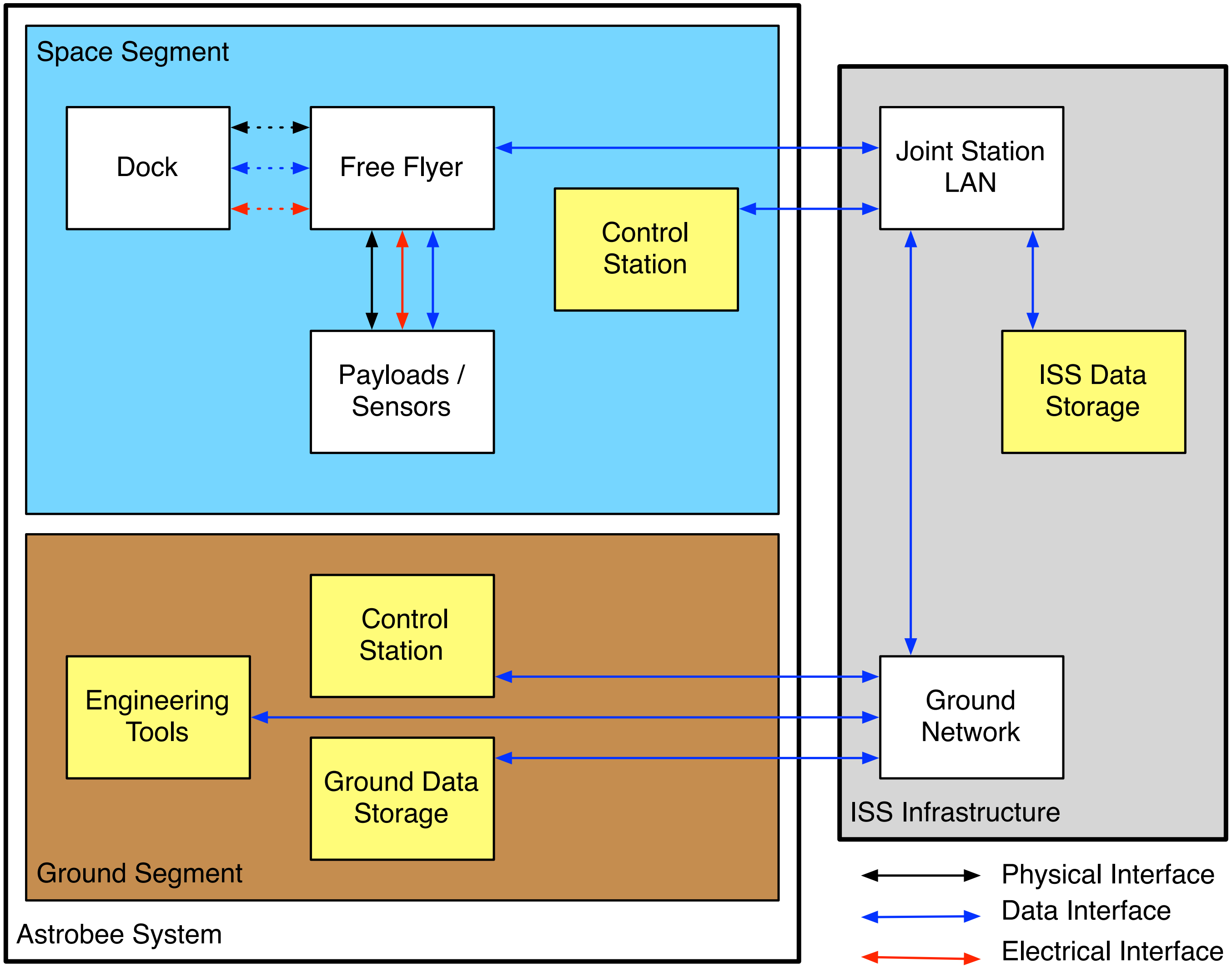
Selected Design

- Eclipse RCP application
- Communicate with Astrobee using RAPID
- Data from Astrobee will be downloaded to an ISS server when Astrobee is in dock, then downlinked
- Streaming video displayed through VLC

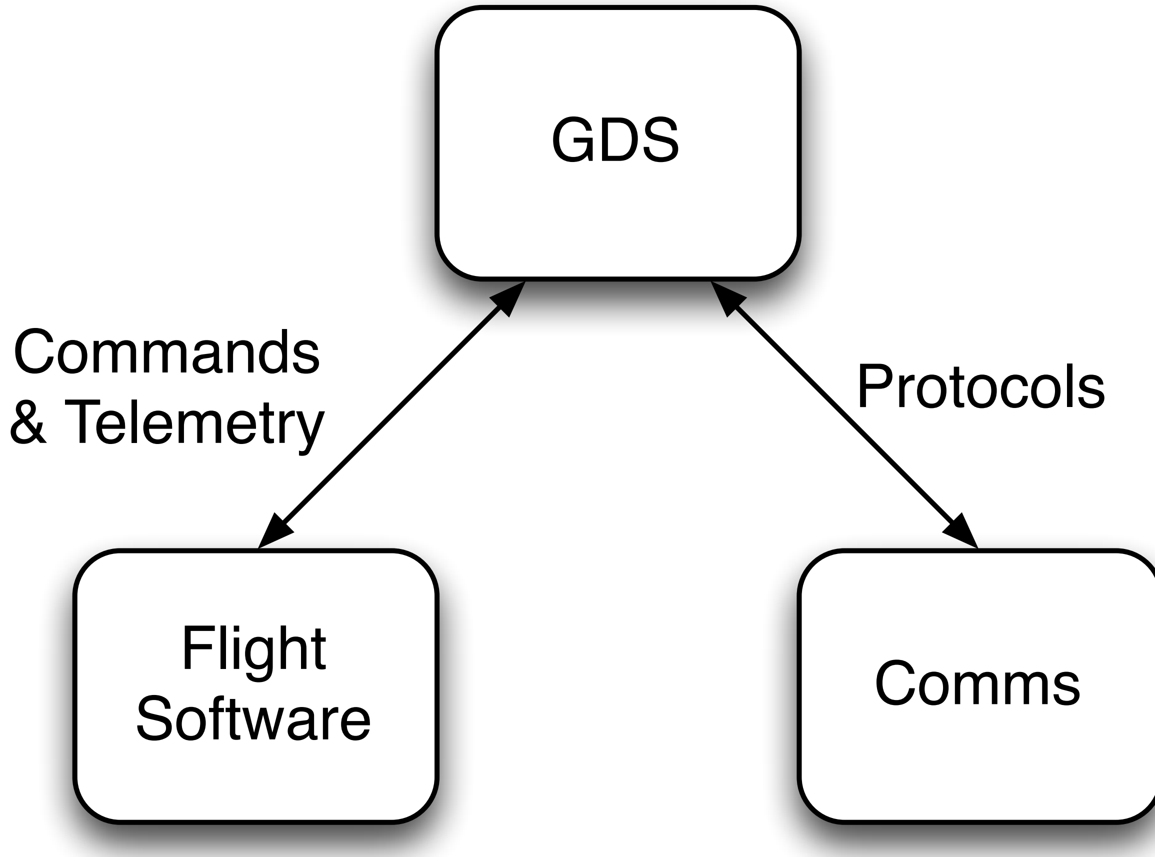
Selected Design

- Pros
  - Allows reuse of much code with “flight heritage”
  - Familiar coding platform
- Cons
  - Messages must be translated from ROS to RAPID on Astrobee
  - Harder to customize look and feel of widgets in Eclipse

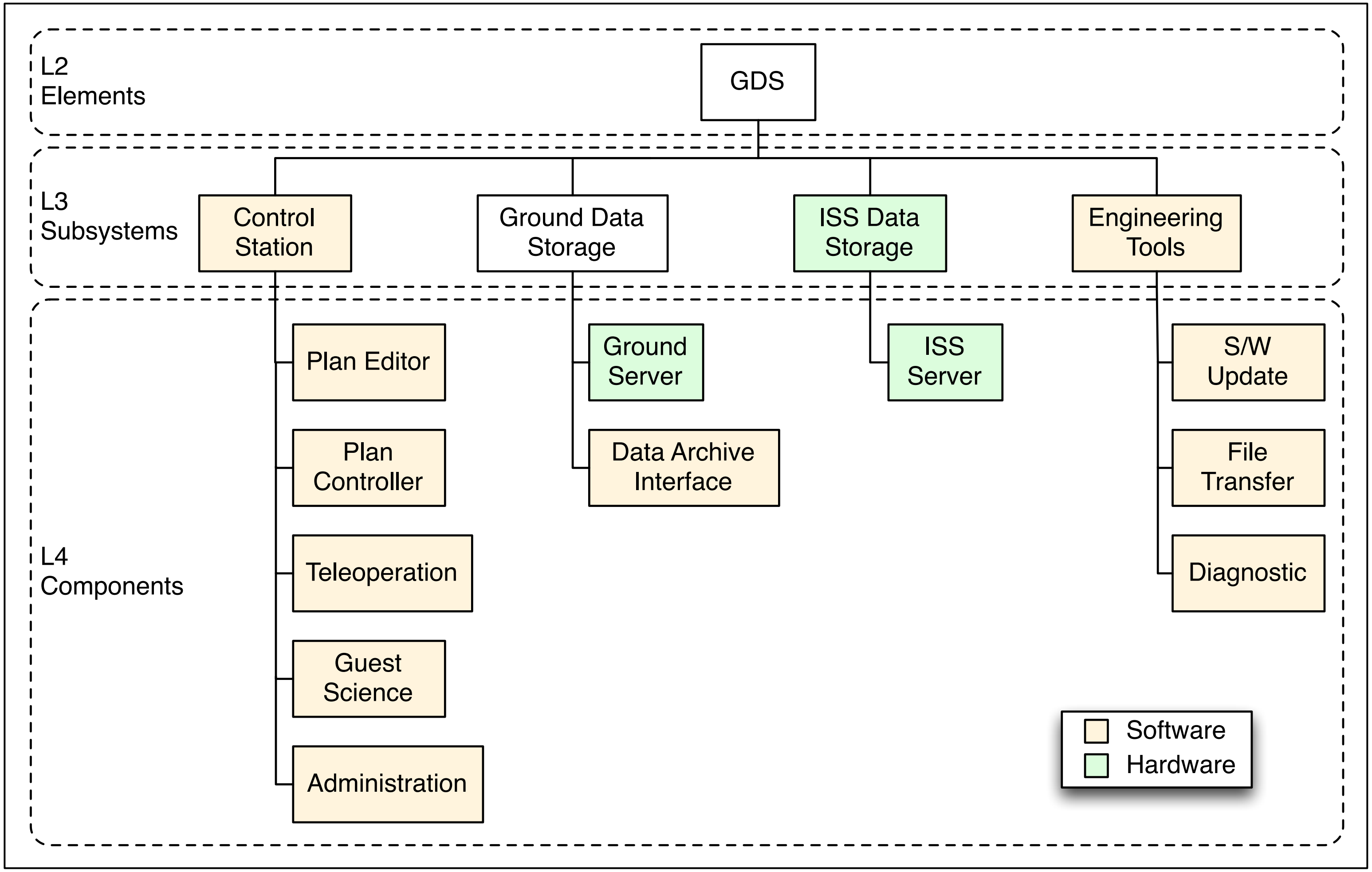
Architecture Diagram



Architecture Diagram



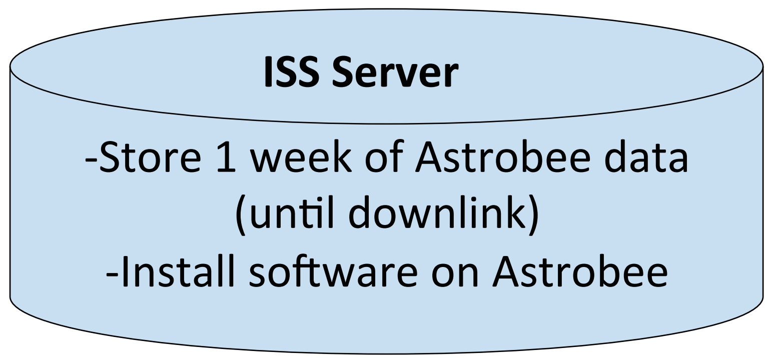
GDS Subsystems



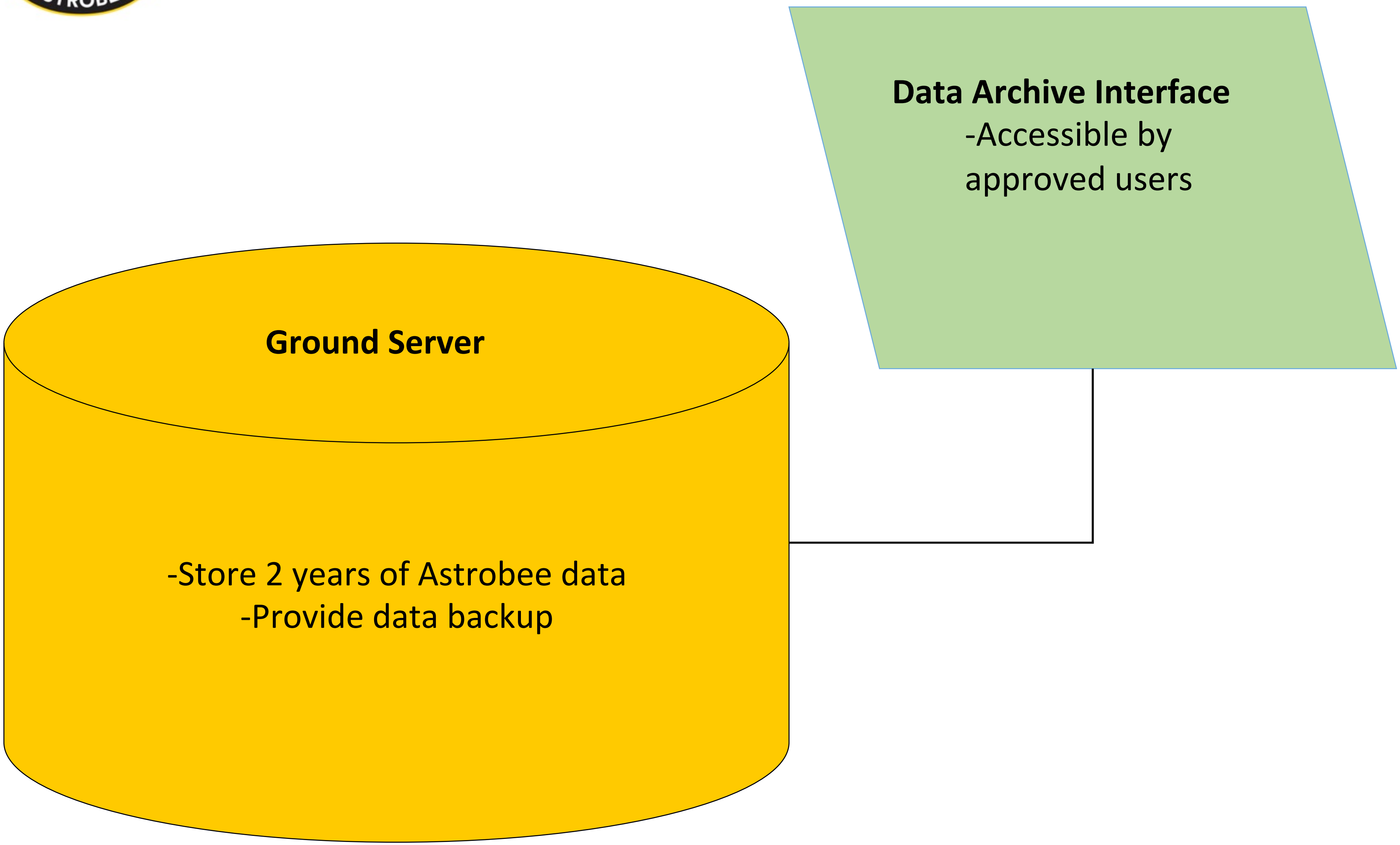
Control Station

Element	Description	Crew	GC	PI
Plan Editor	Create and edit plans		X	X
Plan Controller	Run plans and monitor execution	X	X	
Teleoperation	Send individual commands		X	
Guest Science	Run science on up to 3 Astrobees	X	X	X
Administration	Modify and monitor admin settings	X	X	X

ISS Data Storage



Ground Data Storage

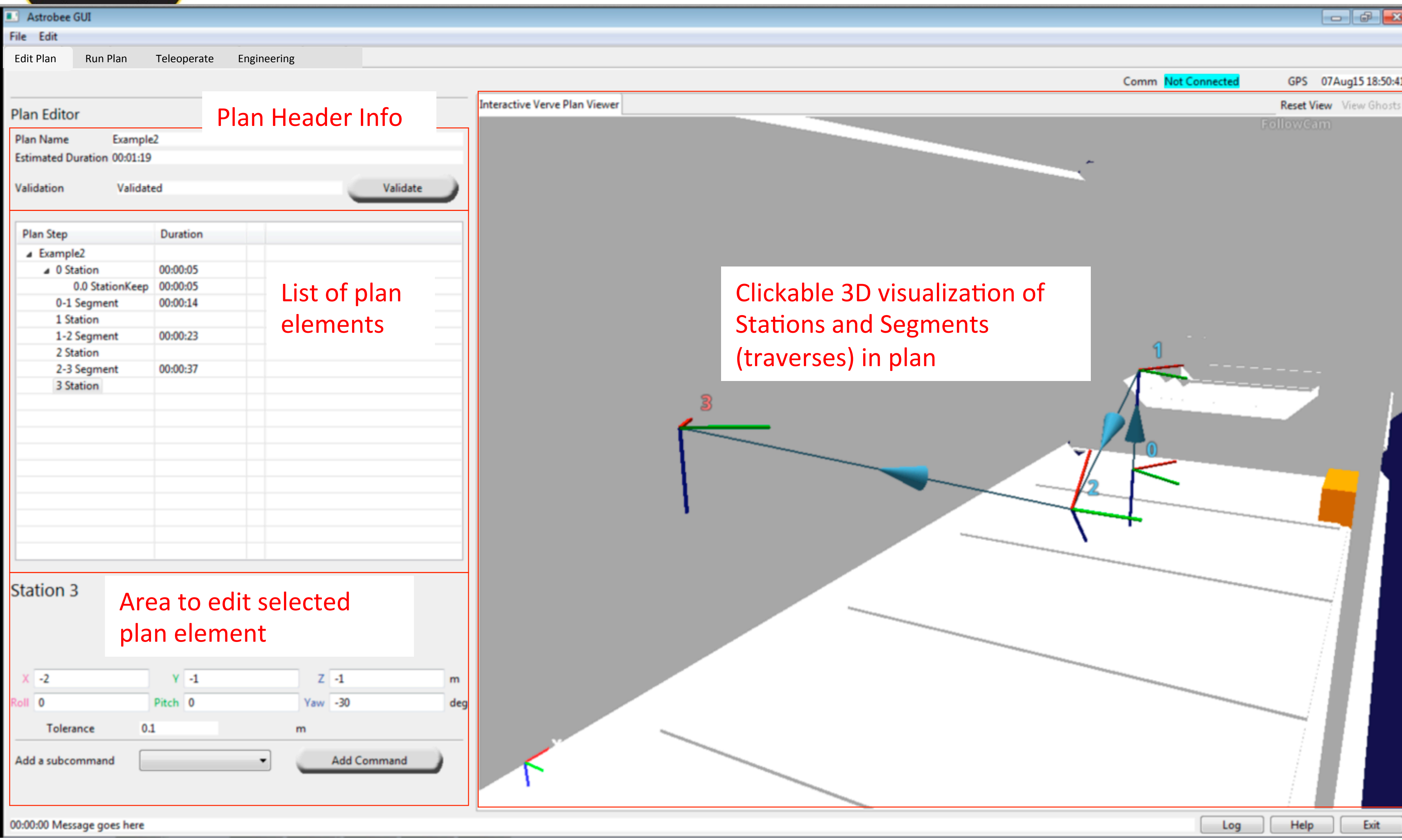


Engineering Tools*

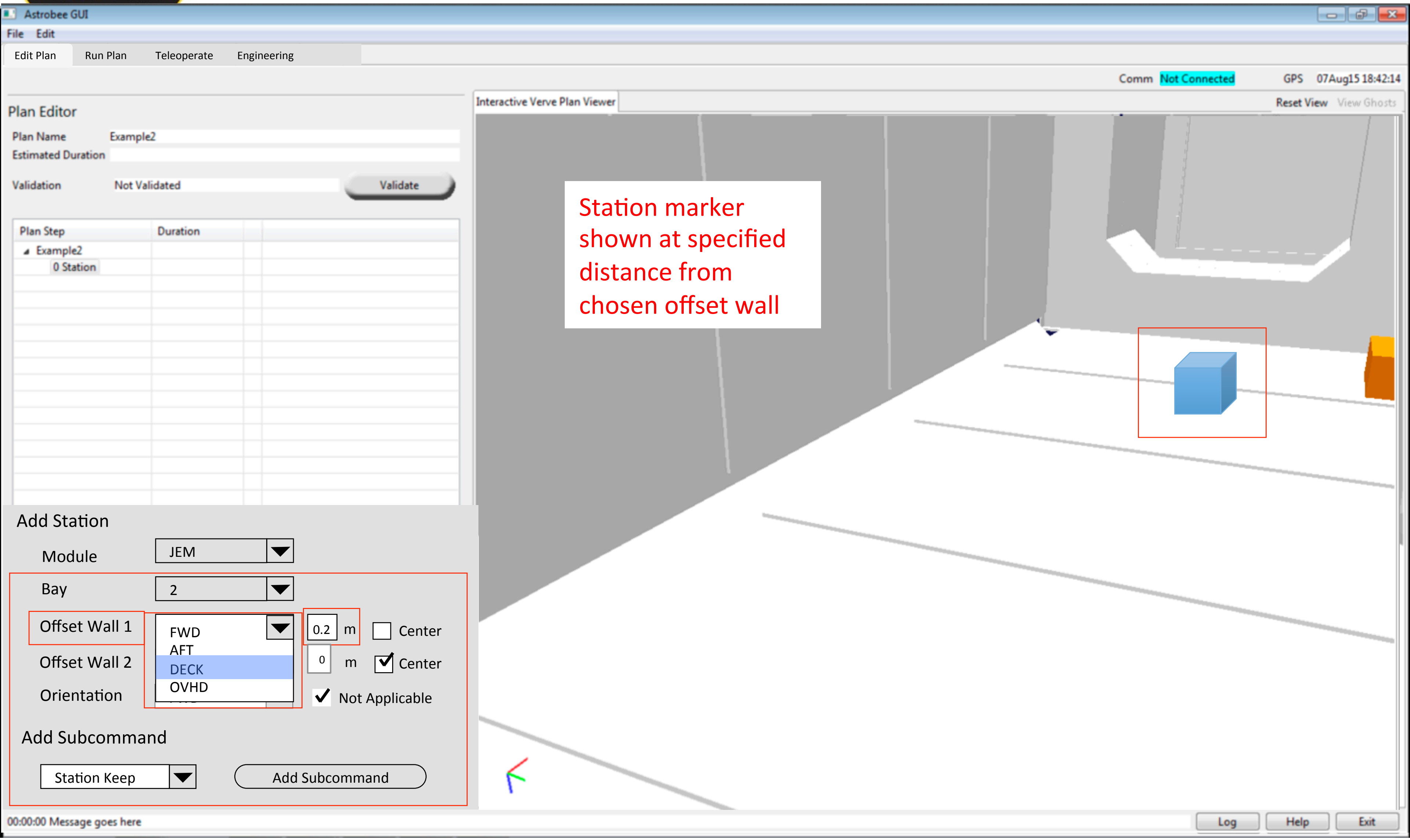
Element	Description
File Transfer	Command line interface to Astrobee
Software Update	Install software on Astrobee
Diagnostic	Display debug telemetry from Astrobee Simulate command execution Display confidence value of Astrobee state estimate

* These are defined as what the FSW team uses as they do development

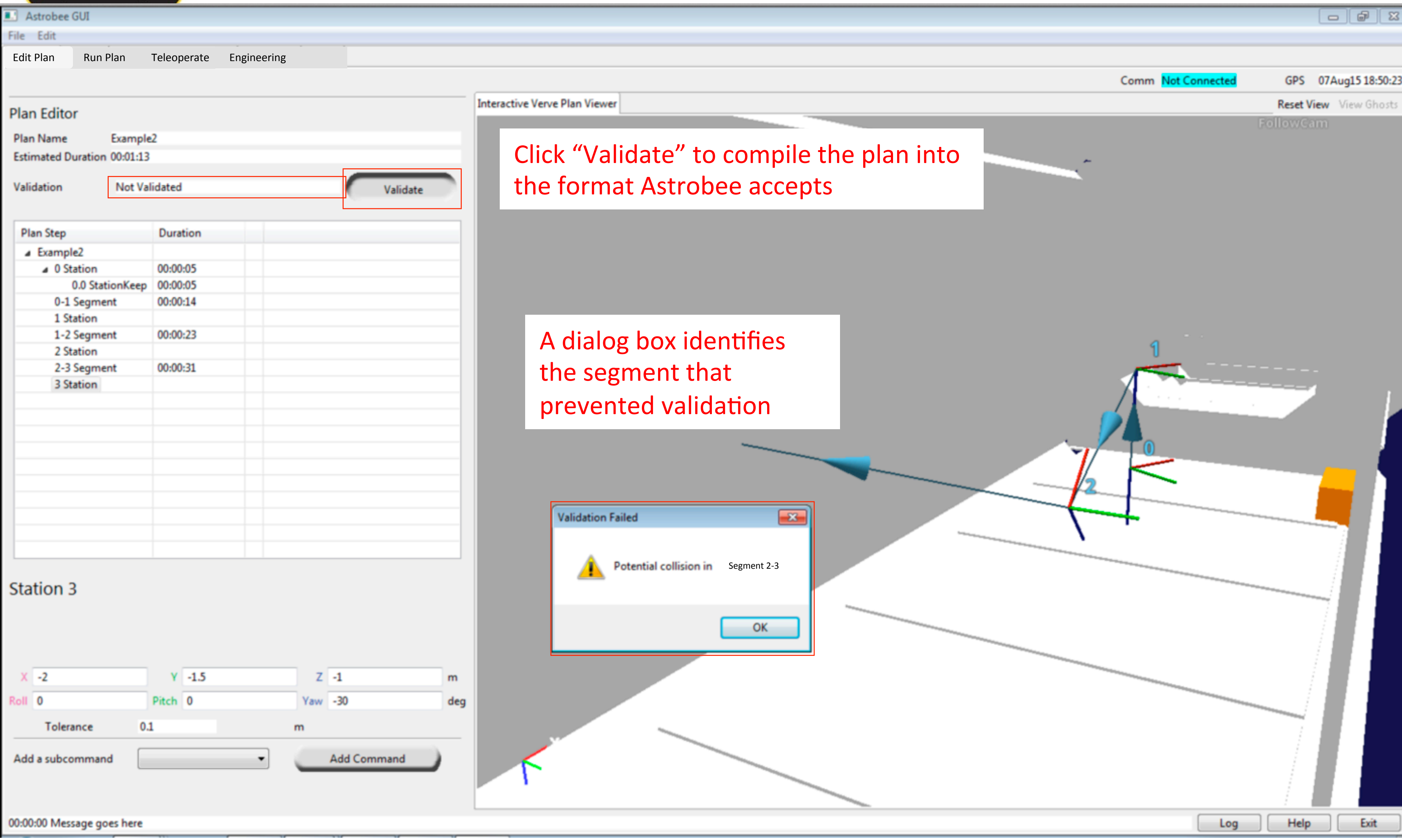
Plan Editor


Astrobee GUI
File Edit
Edit Plan
Run Plan
Teleoperate
Engineering
Comm Not Connected
GPS 07Aug15 18:50:41
Plan Editor
Plan Header Info
Plan Name Example2
Estimated Duration 00:01:19
Validation Validated
Validate
Plan Step
Duration
Example2
0 Station 00:00:05
0.0 StationKeep 00:00:05
0-1 Segment 00:00:14
1 Station
1-2 Segment 00:00:23
2 Station
2-3 Segment 00:00:37
3 Station
List of plan elements
Station 3
Area to edit selected plan element
X -2
Y -1
Z -1
m
Roll 0
Pitch 0
Yaw -30
deg
Tolerance 0.1
m
Add a subcommand
Add Command
Interactive Verve Plan Viewer
Reset View
View Ghosts
FollowCam
Clickable 3D visualization of Stations and Segments (traverses) in plan
0
1
2
3
00:00:00 Message goes here
Log
Help
Exit

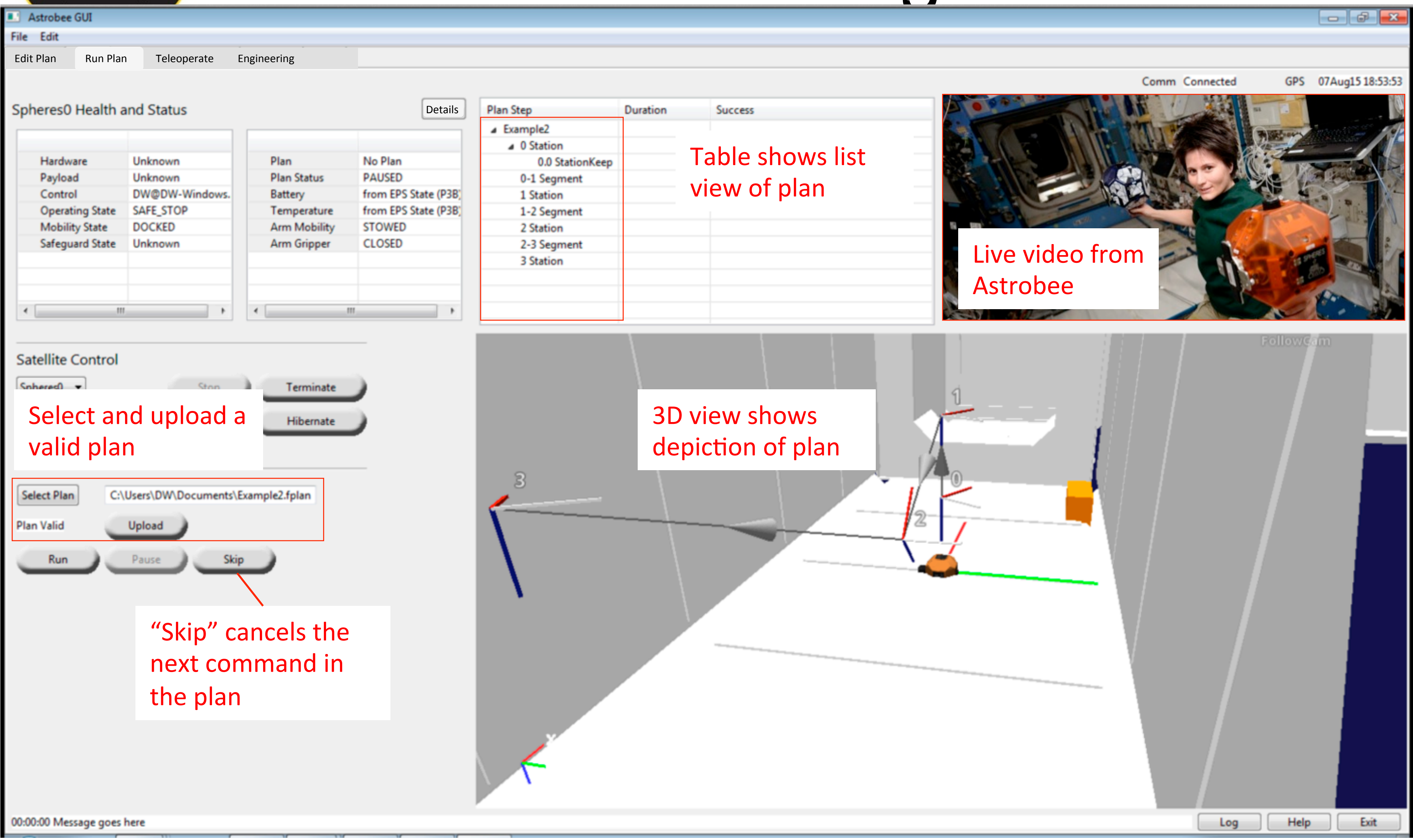
Plan Editor


Astrobee GUI
File Edit
Edit Plan
Run Plan
Teleoperate
Engineering
Comm Not Connected
GPS 07Aug15 18:42:14
Plan Editor
Plan Name Example2
Estimated Duration
Validation Not Validated
Validate
Plan Step
Duration
Example2
0 Station
Interactive Verve Plan Viewer
Reset View
View Ghosts
Station marker shown at specified distance from chosen offset wall
Add Station
Module JEM
Bay 2
Offset Wall 1
FWD
AFT
DECK
OVHD
0.2 m
Center
Offset Wall 2
0 m
Center
Orientation
Not Applicable
Add Subcommand
Station Keep
Add Subcommand
00:00:00 Message goes here
Log
Help
Exit

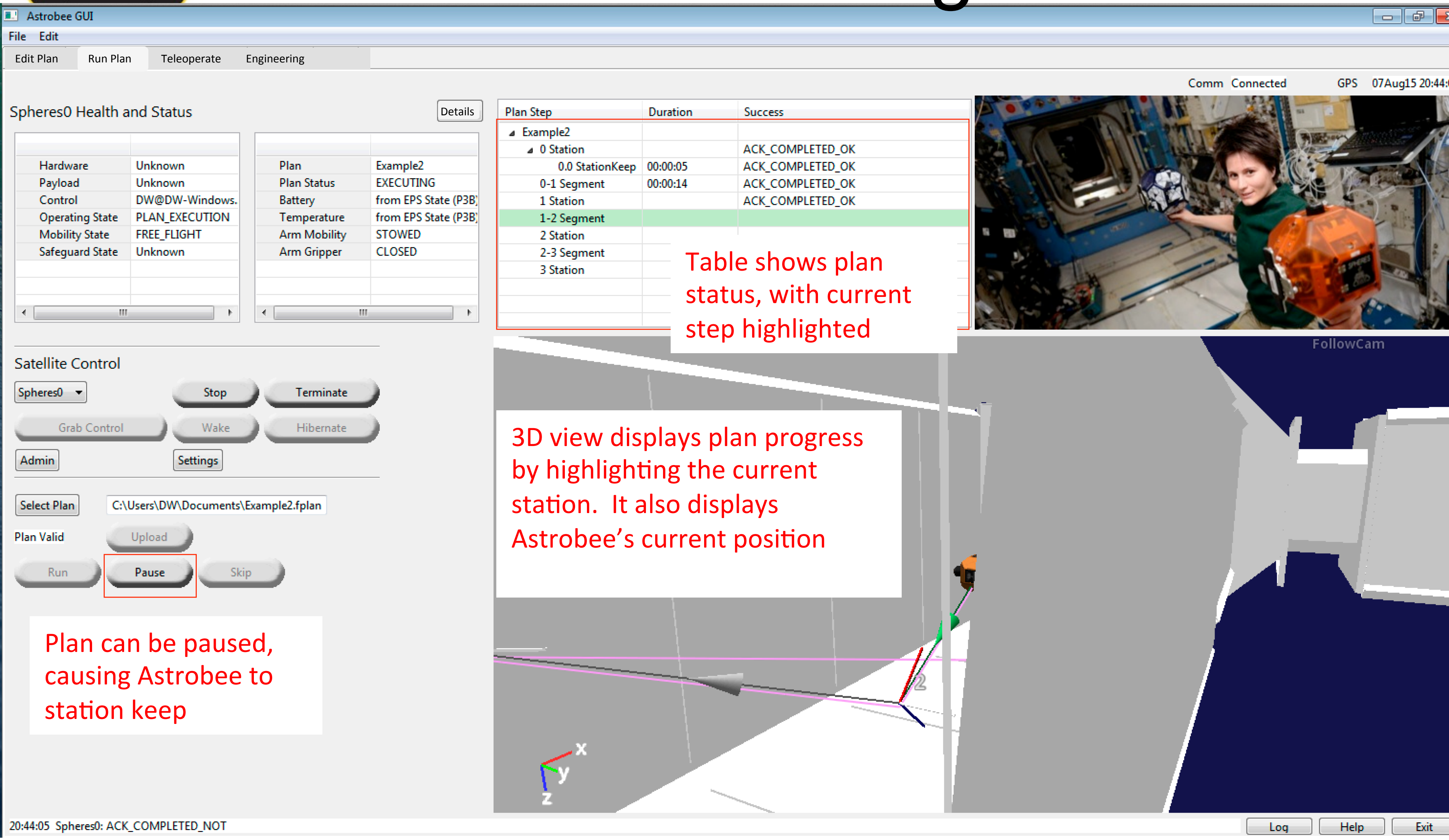
Plan Editor


Astrobee GUI
File Edit
Edit Plan
Run Plan
Teleoperate
Engineering
Comm Not Connected
GPS 07Aug15 18:50:23
Plan Editor
Plan Name Example2
Estimated Duration 00:01:13
Validation Not Validated
Validate
Plan Step
Duration
Example2
0 Station 00:00:05
0.0 StationKeep 00:00:05
0-1 Segment 00:00:14
1 Station
1-2 Segment 00:00:23
2 Station
2-3 Segment 00:00:31
3 Station
Station 3
X -2 Y -1.5 Z -1 m
Roll 0 Pitch 0 Yaw -30 deg
Tolerance 0.1 m
Add a subcommand
Add Command
00:00:00 Message goes here
Interactive Verve Plan Viewer
Reset View
View Ghosts
FollowCam
Click "Validate" to compile the plan into the format Astrobee accepts
A dialog box identifies the segment that prevented validation
Validation Failed
Potential collision in Segment 2-3
OK
Log
Help
Exit

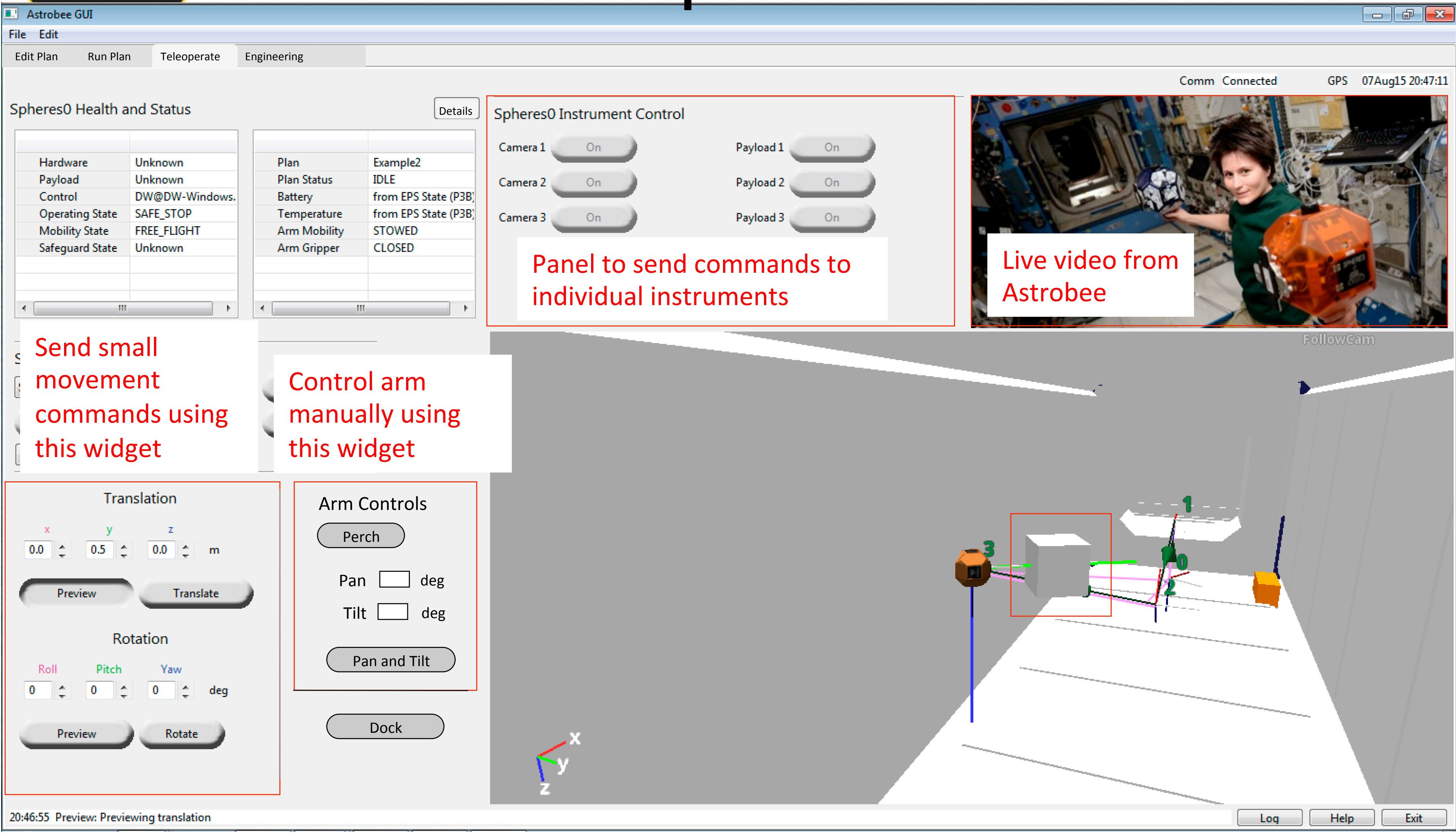
Plan Running



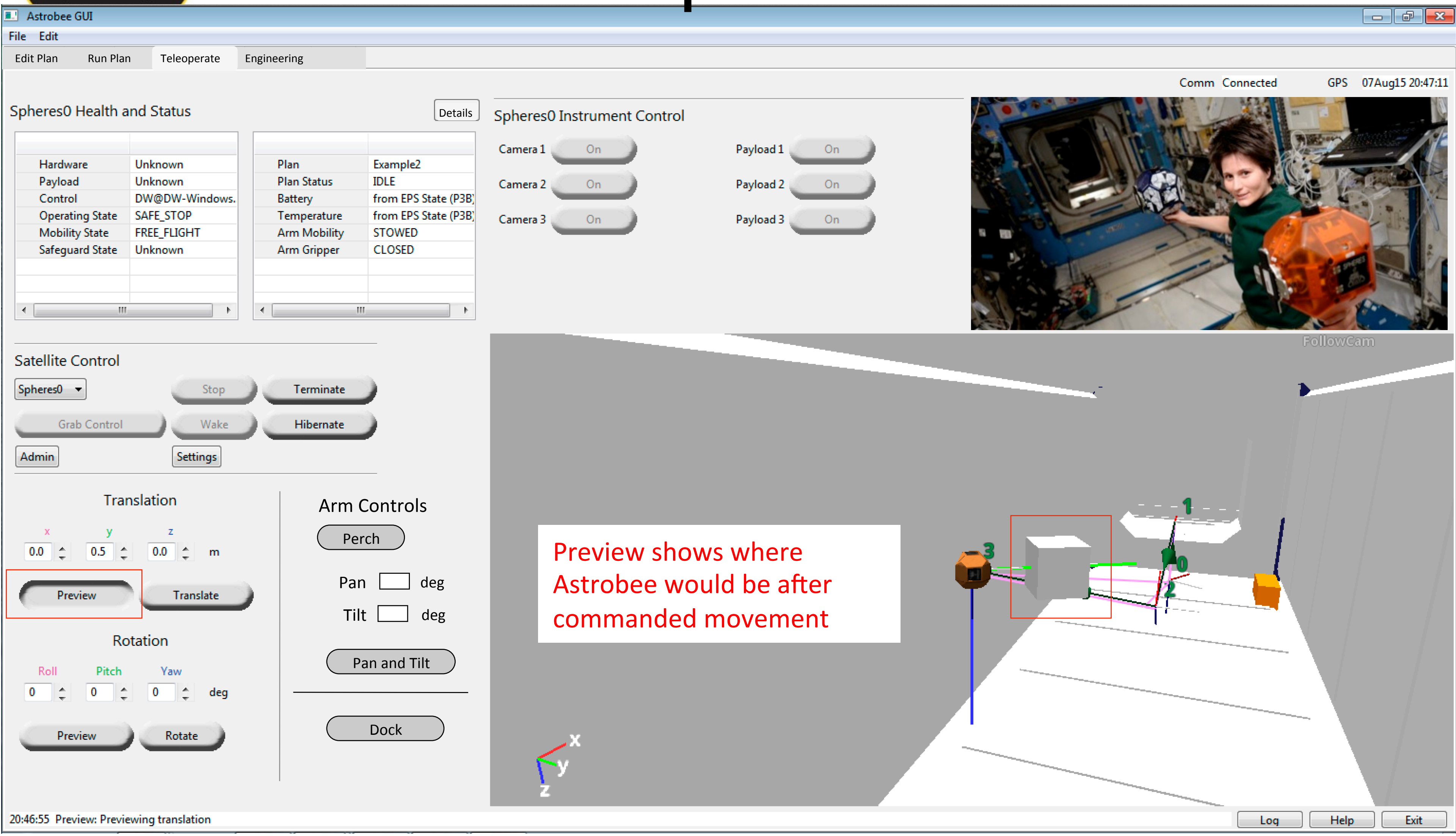
Plan Running



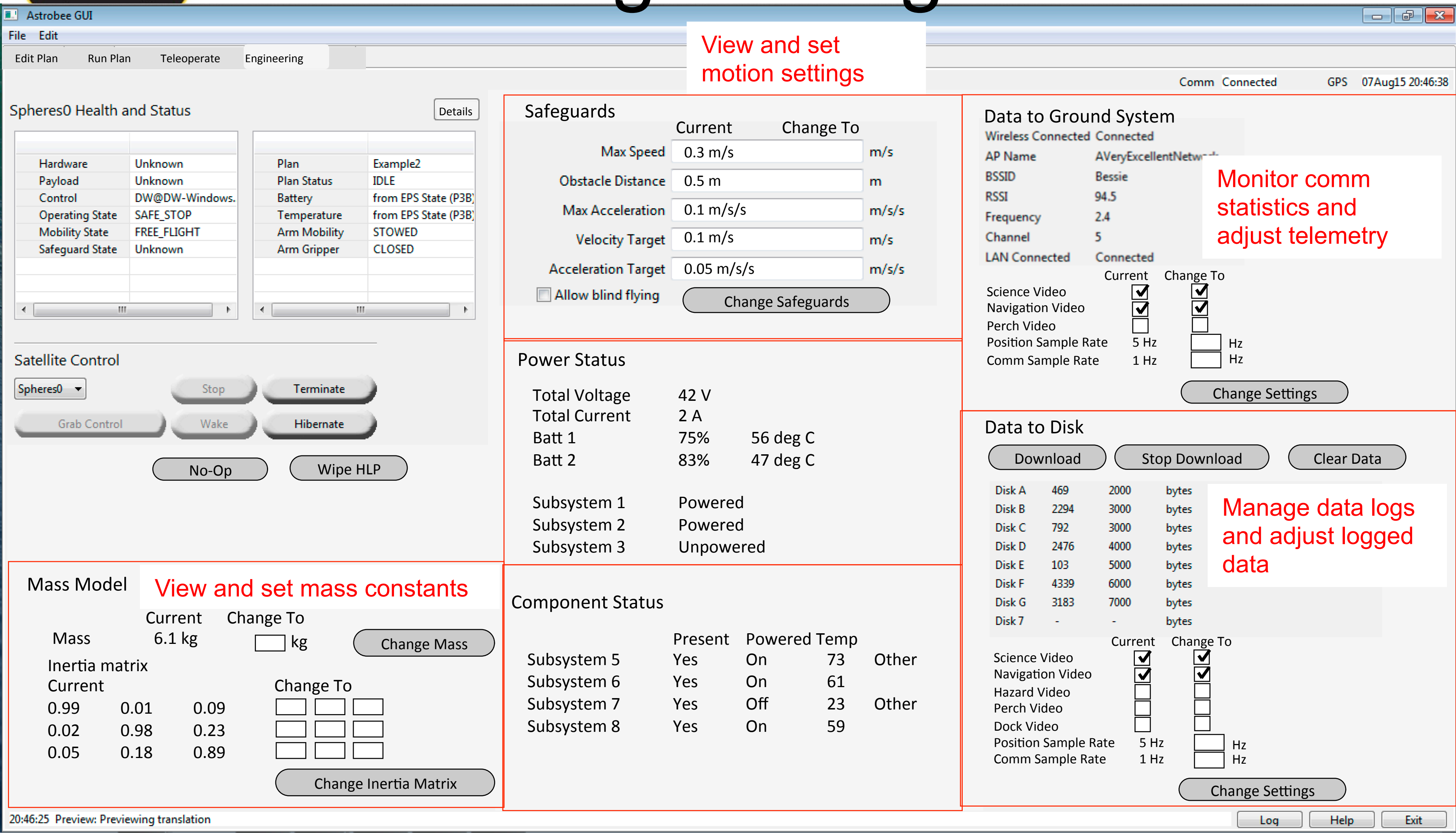
Teleoperation



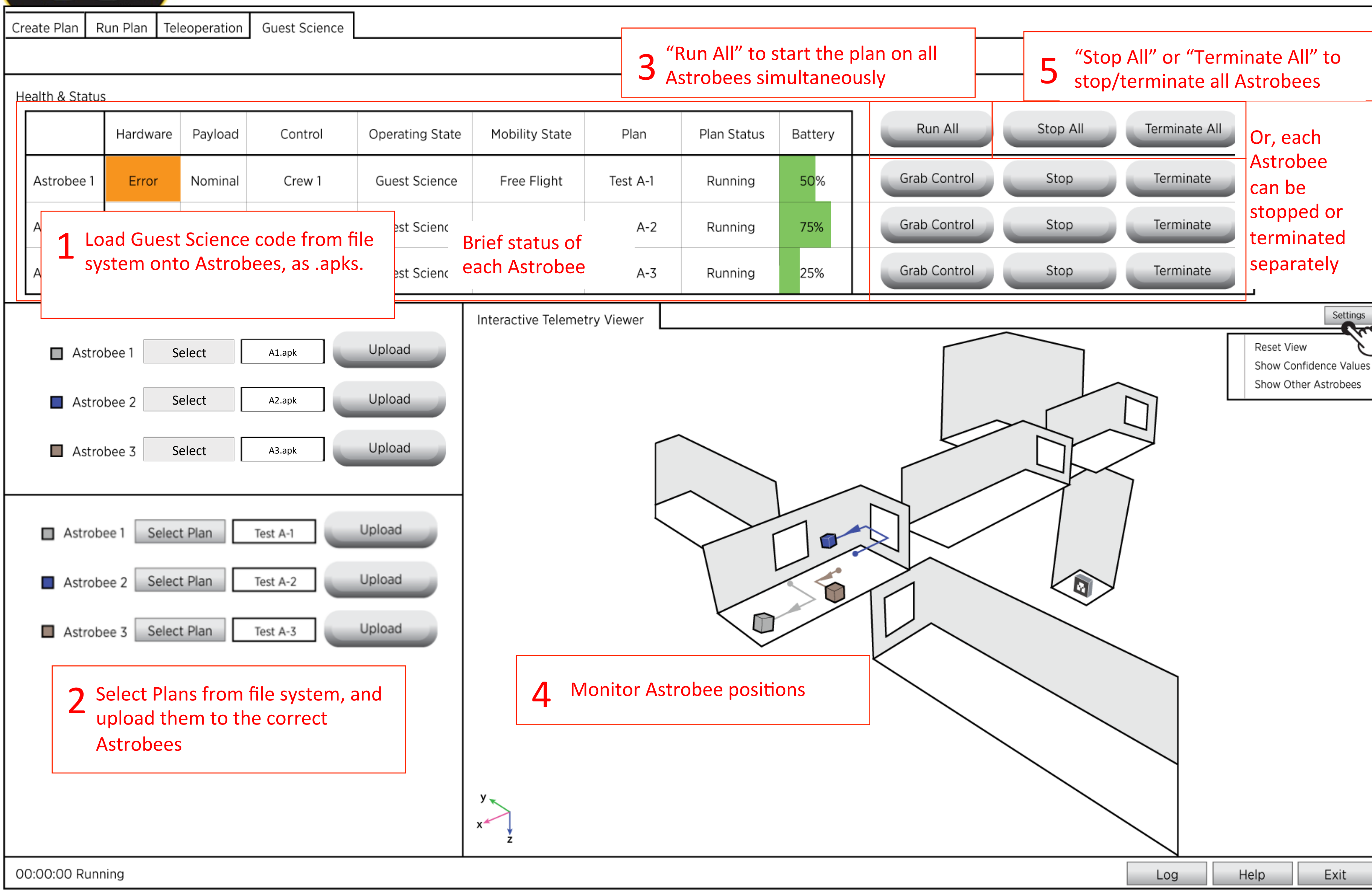
Teleoperation



Engineering



Guest Science



Third Party Software

- Apache – IO, String, Date manipulation
- Ardor3D – 3d graphics
- Codehaus Jackson – parsing JSON
- Eclipse – Application framework
- Javax.media – used by Ardor3D
- Javax.vecmath – used by Rapid framestore
- JDOM – used by Ardor3D
- LWJGL – used by Ardor3D
- RTI – DDS implementation
- VLCJ – video streaming (VLC for Java)

Software Re-use

- RAPID – Communications layer on DDS
- VERVE – 3D visualization
- XPJSON – Plan format used by SmartSPHERES and XGDS
- Design informed by SPHERES Workbench