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 Astrobotee 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

Sensing and Manipulation

Batteries

Core Avionics

Propulsion

Guest Payloads
Or More Poetically

“Sideways Hamburger”
Basic Packaging

PROPULSION MODULE

CENTRAL MODULE

Sensing and Manipulation

Aft Guest Payload

Forward Guest Payload

Batteries x2

Batteries x2

FORWARD
Basic Packaging

PROPULSION MODULE

FRONT VIEW

CENTRAL MODULE

Sensing and Manipulation

Aft Guest Payload

Forward Guest Payload

SIDE VIEW

FORWARD
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

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<td>• Ultem</td>
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Selected Design

• Aluminum structure
  • Pros: strong
  • Cons: requires machining

• Capture Screws
  • Pros: can be used at all module levels
  • Cons: requires tools
## Modularity

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Complete breakdown is on SVN - TBD
# Geometry

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<td>NavCam</td>
<td>Camera axis shall be pitched upward 30 degrees relative to forward motion direction; FOV shall be 90% clear</td>
<td>Forward Top Bay</td>
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<tr>
<td>SciCam</td>
<td>Camera axis shall be aligned with forward motion direction; FOV shall be 100% clear</td>
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<td>Crew Touch Screen</td>
<td>Crew member with face in view of payload camera should be able to use the touch screen display effectively</td>
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<td>HazCam</td>
<td>Camera axis shall be aligned with forward motion direction; FOV shall be 90% clear</td>
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<td>Perching Arm</td>
<td>Shall be able to point SciCam in pan/tilt axes with arm motion</td>
<td>Aft Top Bay</td>
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<td>DockCam</td>
<td>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.</td>
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<td>PerchCam</td>
<td>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.</td>
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<td>Dock Adapter</td>
<td>Dock adapter should be on face to make best use of space (stick out less from wall)</td>
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<tr>
<td>SpeedCam</td>
<td>Camera axis shall be aligned with nominal &quot;up&quot; direction (usually pointing toward overhead); FOV shall be 100% clear</td>
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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

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Options</th>
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<tr>
<td>Propulsion type</td>
<td>• Axial fan&lt;br&gt;• Compressed air&lt;br&gt;• Blower system</td>
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<tr>
<td>Blower diameter</td>
<td>• 4, 4.4, 4.6, and 5 inch</td>
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<tr>
<td>Blower height</td>
<td>• 2 inch&lt;br&gt;• 1 5/8 inch</td>
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<tr>
<td>Nozzle flapper</td>
<td>• Single flapper&lt;br&gt;• Double flapper</td>
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<tr>
<td>Nozzle open area</td>
<td>• 2 cm²&lt;br&gt;• 4 cm²</td>
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<tr>
<td>Nozzle efficiency</td>
<td>• Guillotine&lt;br&gt;• Flapper</td>
</tr>
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</table>
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

- EPS
- GNC Control
- Blower
- Nozzle x8
- PMC
- Plenum

Power: Red
I²C: Blue
x2
Layout

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<thead>
<tr>
<th>Pure Force or Moment Axis</th>
<th>Nozzles Required</th>
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Kistler Axes
## Component List

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<td>Motor Plate</td>
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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 I²C 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 I²C bus
  - 1 x USB 3.0
  - 2 x USB 2.0
  - MIPI DSI + CSI
  - GPIO
Avionics Stack – Side View

5.6 inches

3.6 inches
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

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<th>Computational Power</th>
<th>Comms</th>
<th>Development Cost (SW)</th>
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LLP – **Wandboard Dual**

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

Bottom

Top

LLP Carrier board

IMU

Wandboard
# MLP & HLP Trade Study

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MLP & HLP – *IFC6501*

- 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

- **Power (W)**
- **Current (A)**
- **Time (Second)**

- **All four cores idle**
- **One core with full load**
- **All four cores with full load**
Idle Power Consumption

**Power (W)**

- Core #1 enabled
- Core #1, #2 enabled
- Core #1, #2, #3 enabled
- All cores enabled

**Current (A)**

- Time (Second)
MLP+HLP Carrier Board

3.6 inches

5.6 inches
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
- $V_{\text{batt}}, \text{GND}$
- 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
Laser Pointer

• Direct Emission Green Laser
• 520 nm
• 0.9 mw
LED Flashlight

- 3.3 V @ 1 A
- 216 lm
- 45° viewing angle
- 127°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

Power
Signal
I²C

Supply Power 9V, 3A

Battery x 4 With SMBus and Thermistor

Unreg V_{batt} 3A x 2

Temperature (6)

Unreg V_{batt} 3A x 4

EPS Board

START SW
ON/OFF SW
INHIBIT SW
E-STOP SW

Backplane Board Power for HLP, MLP, LLP, USB, and 2 Spare. One I2C connected to the uPs the Others for sensors.
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 $V_{\text{batt}}$ @ 3A MAX.
  • 4 power lines with Unreg $V_{\text{batt}}$ @ 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

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Array</td>
<td>4S1P</td>
</tr>
<tr>
<td>Voltage</td>
<td>$V_{\text{max}} = 16.8\text{V}, V_{\text{nom}} = 14.4\text{V}, V_{\text{cutoff}} = 9.6\text{V}$</td>
</tr>
<tr>
<td>Max Discharge Current</td>
<td>4A</td>
</tr>
<tr>
<td>Max Continuous Power</td>
<td>40W</td>
</tr>
<tr>
<td>Weight</td>
<td>234 g</td>
</tr>
<tr>
<td>Comm</td>
<td>SMBus</td>
</tr>
<tr>
<td>Dimension</td>
<td>23 mm x 87 mm x 79 mm</td>
</tr>
</tbody>
</table>
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)
• 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)
## Component List

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Purpose</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>NavCam</td>
<td>Localization – Optical flow, Sparse Mapping</td>
<td>Forward</td>
</tr>
<tr>
<td>DockCam</td>
<td>Localization – AR tag extraction</td>
<td>Aft</td>
</tr>
<tr>
<td>SciCam</td>
<td>HD video streaming and recording</td>
<td>Forward</td>
</tr>
<tr>
<td>SpeedCam</td>
<td>Localization – Optical flow</td>
<td>Up</td>
</tr>
<tr>
<td>HazCam</td>
<td>Obstacle avoidance</td>
<td>Forward</td>
</tr>
<tr>
<td>PerchCam</td>
<td>Handrail detection</td>
<td>Aft</td>
</tr>
</tbody>
</table>
Sensor Layout

- DockCam
- PerchCam
- NavCam
- SpeedCam
- HazCam
- SciCam
NavCam & DockCam

• 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: $54.8^\circ \times 42.5^\circ$
- $38.1 \times 30.5 \times 1.5 \text{ mm}$, $5 \text{ g}$
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° x 45°, 224 x 172 pixels
HazCam & PerchCam

2D Projection → 3D Depth
Comms
Team

• Ted Morse
• Vinh To
• Jason Lum (alum)
Comms Block Diagram

ISS

Astrobee
- Internal Switch
- LLP
- MLP
- HLP
- Payload

Dock

Crew Control Station

Storage

Ku-Band

Ethernet/LAN
- Ethernet: Internal IP
- Ethernet: Internal and External IP
- WiFi: External IP
- USB

ARC MMOC
- Storage
- Operator/Engineer Control

MSFC POIC
- Operator Control

JSC MCC
- Operator Control

White Sands
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 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)

Ground Data System

DDS Messages

Fault Manager

Sequencer

MLP Executive

MLP

Obstacle Detection

Optical Flow

Sparse Mapping Loc.

DepthMap (Perch) Loc.

AR Tag (Dock) Localization

Pose Estimator

Control

EPS

GN&C

Fault Manager

All Nodes States

Ground Data System

DDS Messages

Fault Manager

Sequencer

MLP Executive

MLP

Obstacle Detection

Optical Flow

Sparse Mapping Loc.

DepthMap (Perch) Loc.

AR Tag (Dock) Localization

Pose Estimator

Control

EPS

GN&C

ARM

NavCam

PerchCam

DockCam

HazCam

ARM

SpeedCam

Propulsion

IMU

All Nodes States

Ground Data System

DDS Messages

Fault Manager

Sequencer

MLP Executive

MLP

Obstacle Detection

Optical Flow

Sparse Mapping Loc.

DepthMap (Perch) Loc.

AR Tag (Dock) Localization

Pose Estimator

Control

EPS

GN&C

ARM

NavCam

PerchCam

DockCam

HazCam

ARM

SpeedCam

Propulsion

IMU
System Architecture (HLP)

Untrusted Guest Science

User Interface

Trusted Guest Science

API

JAVA Interface

Guest Payloads

Speakers

Touch Screen

Microphone

Science Cam.

Video Manager

Ground Data System

Sequencer

MLP Executive

ROS Java

HLP

MLP

JAVA Interface

ROS Java
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

|-------------------------------|--------------------------------|----------------------------------------|-----------------------------------------------|--------------------------|-------------------------------|

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.
Localization Design Drivers

Localization Options

<table>
<thead>
<tr>
<th>Infrastructure + External Maps</th>
<th>ISS Wifi</th>
<th>Does not provide desired accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beacons (passive/active)</td>
<td>Modifications to ISS / change dependent</td>
</tr>
<tr>
<td>Robot Builds Maps</td>
<td>Stereo Vision</td>
<td>“Metric” (shape) maps makes matching difficult</td>
</tr>
<tr>
<td></td>
<td>3D sensors (LIDAR, ...)</td>
<td>“Features” maps efficient to filter</td>
</tr>
<tr>
<td></td>
<td>Monocular Vision</td>
<td></td>
</tr>
</tbody>
</table>

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 features from images to features in 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

<table>
<thead>
<tr>
<th>OS Selection Criteria</th>
<th>Localization Selection Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modularity</td>
<td>Measurement Rate</td>
</tr>
<tr>
<td>Service Isolation</td>
<td>Robust Against Drift</td>
</tr>
<tr>
<td>Messaging Performance</td>
<td>Robust Against Occlusion</td>
</tr>
<tr>
<td>Usability / Familiarity</td>
<td>Robust Against Env. Change</td>
</tr>
<tr>
<td>Works on Target and Host</td>
<td>Algorithm Simplicity</td>
</tr>
<tr>
<td>Record/Playback raw data</td>
<td>Implementation Available</td>
</tr>
<tr>
<td>Maturity</td>
<td>Localization Initialization</td>
</tr>
<tr>
<td>Open Source</td>
<td>Target Platform</td>
</tr>
</tbody>
</table>
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
100 Hz


Waypoints <5 Hz

Mid-Level Processor (MLP) OR GN&C MLP Simulator

Computer Vision System OR Computer Vision System
Waypoint Cmd Sequencer OR Waypoint Cmd Sequencer

Low-Level Processor (LLP)

Serial Comm

GN&C Robot Simulator

Vehicle Dynamics, IMU, Propulsion Module, Environmental Model

OR
GN&C
HW Components- IMU

• Epson G362
  FEATURES
  - Small Size, Lightweight
  - Low-Noise, High-stability
    - Gyro Bias Instability
    - Angular Random Walk
  - Initial Bias Error
  - 6 Degrees Of Freedom
    - Triple Gyrosopes
    - Tri-Axis Accelerometer
  - 16/32bit data resolution
  - Digital Serial Interface
  - 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
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
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

Each State Command Defines a Trajectory
Command Converges to Trajectory
Limits Enforced
GN&C: SW Components
Command Shaper (CMD)

Mid-Level Processor

Low-Level Processor

Re-compute triggered if:
1) Increase in KF confidence
2) Attitude/Position error exceeds threshold

Trajectory Command = Two waypoints, current and future

\((t_n, \bar{r}_n, \bar{v}_n, \bar{a}_n, Q_n, \bar{\omega}_n, \bar{\alpha}_n), (t_{n+1}, \bar{r}_{n+1}, \bar{v}_{n+1}, \bar{a}_{n+1}, Q_{n+1}, \bar{\omega}_{n+1}, \bar{\alpha}_{n+1})\)

EST state

Time Varying Command State Vector

\(\bar{r}(t), Q(t), \bar{v}(t), \bar{\omega}(t)\)
GN&C: SW Components
Control (CTL)
GN&C: SW Components
Force Allocation Module (FAM)

Mode Command

Set Impeller Speed

Lookup Table: Total Thrust -> Delta Pressure

Convert to Nozzle Thrust Commands

Calculate Needed Nozzle Opening Area

Convert Nozzle Area to Servo Command

Nozzle Servo Commands

Impeller Speed Command

Body Force and Torque Commands from CTL

Convert to Nozzle Area

Calculate Needed Nozzle Opening Area

Convert Nozzle Area to Servo Command

Nozzle Servo Commands
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

Environment Model:
- Rigid Body Dynamics
- Disturbance Model
- Time Model

MLP Model:
- Vision Model
- Sequencer Model

Vehicle Model:
- IMU Model
- Propulsion Model
- EPS Model

Actuator Commands

Output to GNC
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
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, 0.000000

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, 0.039753

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, 0.025925

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
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)
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)
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

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

- 240 mm
- 80 mm
- 80 mm
# Mechanical Mass

<table>
<thead>
<tr>
<th></th>
<th>Base Link</th>
<th>Tilt Joint</th>
<th>Forearm Link</th>
<th>Pan Joint</th>
<th>Gripper</th>
<th>Total [g]</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aluminum</strong></td>
<td>14.89</td>
<td>102.18</td>
<td>21.95</td>
<td>103.84</td>
<td></td>
<td>242.86</td>
<td>0.002712 g/mm³</td>
</tr>
<tr>
<td><strong>Ultem 2300</strong></td>
<td>8.29</td>
<td>68.86</td>
<td>12.22</td>
<td>69.78</td>
<td></td>
<td>159.15</td>
<td>0.00151 g/mm³</td>
</tr>
<tr>
<td><strong>Ultem 9085</strong></td>
<td>7.36</td>
<td>64.15</td>
<td>10.85</td>
<td>64.97</td>
<td></td>
<td>147.33</td>
<td>0.00134 g/mm³</td>
</tr>
<tr>
<td><strong>Plastic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>110.00</td>
<td>110.00</td>
<td>From P3 gripper</td>
</tr>
<tr>
<td><strong>1.</strong> Aluminum Case Arm + Plastic Case Gripper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>352.86</td>
<td></td>
</tr>
<tr>
<td><strong>2.</strong> Ultem 2300 Case Arm + Plastic Case Gripper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>269.15</td>
<td></td>
</tr>
<tr>
<td><strong>3.</strong> Ultem 9085 Case Arm + Plastic Case Gripper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>257.33</td>
<td></td>
</tr>
</tbody>
</table>

- 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 Astrobot structural mass
  - Assumed micro-gravity environment (9.8E-6 m/s²)
- 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

- Joint Position [deg]
- Joint Velocity [deg/sec]
- Joint Acceleration [deg/(sec²)]
- Torque [Nm]

Time Step [1 step = 0.1 sec]

Joint Position [deg] vs. Time Step [1 step = 0.1 sec]
- θ₁, θ₂

Joint Velocity [deg/sec] vs. Time Step [1 step = 0.1 sec]
- θ₁, θ₂
- 11.25°/sec

Joint Acceleration [deg/(sec²)] vs. Time Step [1 step = 0.1 sec]
- θ₁, θ₂
- 2.31°/sec²

Torque [Nm] vs. Time Step [1 step = 0.1 sec]
- τ₁, τ₂
- 23.3 mNm
Motor Selection

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

### Specifications

<table>
<thead>
<tr>
<th>reduction ratio (rounded)</th>
<th>output speed up to $n_{max}$ rpm</th>
<th>weight with motor g</th>
<th>output torque continuous operation $M_{max}$ mNm</th>
<th>output torque intermittent operation $M_{max}$ mNm</th>
<th>direction of rotation (reversible)</th>
<th>efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 : 1</td>
<td>635</td>
<td>25</td>
<td>9</td>
<td>30</td>
<td>=</td>
<td>81</td>
</tr>
<tr>
<td>22 : 1</td>
<td>223</td>
<td>26</td>
<td>23</td>
<td>75</td>
<td>≠</td>
<td>73</td>
</tr>
<tr>
<td>33 : 1</td>
<td>151</td>
<td>26</td>
<td>30</td>
<td>100</td>
<td>=</td>
<td>66</td>
</tr>
<tr>
<td><strong>112 : 1</strong></td>
<td><strong>44</strong></td>
<td><strong>27</strong></td>
<td><strong>93</strong></td>
<td><strong>180</strong></td>
<td>≠</td>
<td><strong>59</strong></td>
</tr>
<tr>
<td>207 : 1</td>
<td>24</td>
<td>27</td>
<td>100</td>
<td>180</td>
<td>=</td>
<td>53</td>
</tr>
<tr>
<td>361 : 1</td>
<td>14</td>
<td>27</td>
<td>100</td>
<td>180</td>
<td>=</td>
<td>53</td>
</tr>
<tr>
<td>814 : 1</td>
<td>6</td>
<td>28</td>
<td>100</td>
<td>180</td>
<td>=</td>
<td>43</td>
</tr>
<tr>
<td><strong>1 257 : 1</strong></td>
<td><strong>4</strong></td>
<td><strong>29</strong></td>
<td><strong>100</strong></td>
<td><strong>180</strong></td>
<td>=</td>
<td><strong>43</strong></td>
</tr>
</tbody>
</table>
✔ [FFREQ-175] The perching arm shall pan at least -90° to 90° out from center while perched.
[FFREQ-175] The perching arm shall tilt at least -30° to 90° out from center while perched.
Perch Cam Location

✔ [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.
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 manually

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

- **Reverse Voltage Protection**
- **Voltage Regulator**
- **ST-Link/V2**
- **Microcontroller**
- **Motor Driver**
- **Motor Board #1**
- **Motor Board #2**
- **Gripper Board**

**Power Lines:**
- 14.4 V
- 6.0 V

**Signal Lines:**
- USB 2.0
- I2C
- Motor PWM
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 of 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
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
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

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lance</td>
<td>• Cone</td>
</tr>
<tr>
<td></td>
<td>• Cone and cylinder</td>
</tr>
<tr>
<td></td>
<td>• Cone, cylinder, and head</td>
</tr>
<tr>
<td>Retention System</td>
<td>• Magnet and linear actuator</td>
</tr>
<tr>
<td></td>
<td>• Electromagnet</td>
</tr>
<tr>
<td>ISS Mounting</td>
<td>• Single Seat track</td>
</tr>
<tr>
<td></td>
<td>• Double Seat Track</td>
</tr>
<tr>
<td></td>
<td>• Velcro</td>
</tr>
</tbody>
</table>
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
Option 1 Drawing

- Magnet – 4X
- Linear Actuator – 2X
- Power /Signal Connector
- Lance -2X
- Battery
- Light Indicator
- Power Connector
- RJ-45 Connector
- ON /Off Switch
- Switch Guard

Detail view
Option 2 Drawing

Side view

Front view
Option 2 Drawing

Electromagnet – 2X

Detail view
Dock Interface

Electromagnet – 2X
Connector – 20 pin
Spring Loaded pin - 20X
Lance – 2X
Astrobee Interface

- Cup – 2X
- Electromagnet striker plate – 2X
- Connector – 20 pin
- Nail Head pin -20X
X-Section Cont.
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
Dock Placement Study
## Component List

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

Design Overview
Subsytem 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

Actuator

Dock Adapter

Dock Adapter

Actuator

Network Switch

AC/DC Converter

Battery Charger

Battery Charger

Charger Board

Controller
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 Astrobbees at 9V @ 3A each

• Network switch to connect Astrobbee to wired LAN

• Mating Dock connector to Astrobbee 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

Space Segment
- Dock
- Free Flyer
- Payloads / Sensors

Ground Segment
- Engineering Tools
- Control Station
- Ground Data Storage

Astrobee System

ISS Infrastructure
- Joint Station LAN
- ISS Data Storage
- Ground Network

Physical Interface
Data Interface
Electrical Interface
GDS Subsystems

L2 Elements

L3 Subsystems
- Control Station
- Ground Data Storage
- ISS Data Storage
- Engineering Tools

L4 Components
- Plan Editor
- Plan Controller
- Teleoperation
- Guest Science
- Administration

GDS

Ground Server

Data Archive Interface

ISS Server

S/W Update

File Transfer

Diagnostic
## Control Station

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
<th>Crew</th>
<th>GC</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan Editor</td>
<td>Create and edit plans</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Plan Controller</td>
<td>Run plans and monitor execution</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Teleoperation</td>
<td>Send individual commands</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guest Science</td>
<td>Run science on up to 3 Astrobotes</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Administration</td>
<td>Modify and monitor admin settings</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
ISS Data Storage

- Store 1 week of Astrobee data (until downlink)
- Install software on Astrobee
Ground Data Storage

- Store 2 years of Astrobee data
  - Provide data backup

Data Archive Interface
  - Accessible by approved users
## Engineering Tools*

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>File Transfer</td>
<td>Command line interface to Astrobee</td>
</tr>
<tr>
<td>Software Update</td>
<td>Install software on Astrobee</td>
</tr>
<tr>
<td>Diagnostic</td>
<td>Display debug telemetry from Astrobee</td>
</tr>
<tr>
<td></td>
<td>Simulate command execution</td>
</tr>
<tr>
<td></td>
<td>Display confidence value of Astrobee state estimate</td>
</tr>
</tbody>
</table>

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

Plan Editor

Plan Header Info

List of plan elements

Clickable 3D visualization of Stations and Segments (traverses) in plan

Area to edit selected plan element
Plan Editor

Station marker shown at specified distance from chosen offset wall
Plan Editor

Click “Validate” to compile the plan into the format Astrobee accepts.

A dialog box identifies the segment that prevented validation.
Plan Running

- **Table shows list view of plan**
- **3D view shows depiction of plan**
- **Live video from Astrobee**
- **Select and upload a valid plan**
- **“Skip” cancels the next command in the plan**

Details

- **Edit Plan**
- **Run Plan**
- **Teleoperate**
- **Engineering**

**Spheres0 Health and Status**

- Hardware
- Payload
- Control
- Operating State
- Mobility State
- Safeguard State

- Plan
- Plan Status
- Battery
- Temperature
- Arm Mobility
- Arm Gripper

**Satellite Control**

- **Terminate**
- **Hibernate**

**Plan Step**

- Example2
- 0 Station Keep
- 0-1 Segment
- 1 Station
- 1-2 Segment
- 2 Station
- 2-3 Segment
- 3 Station
Plan Running

Table shows plan status, with current step highlighted

3D view displays plan progress by highlighting the current station. It also displays Astrobotee’s current position

Plan can be paused, causing Astrobotee to station keep
Teleoperation

Panel to send commands to individual instruments

Live video from Astrobee

Send small movement commands using this widget

Control arm manually using this widget
Teleoperation

Preview shows where Astrobee would be after commanded movement
Guest Science

1. Load Guest Science code from file system onto Astrobees, as .apks.

2. Select Plans from file system, and upload them to the correct Astrobees

3. "Run All" to start the plan on all Astrobees simultaneously

4. Monitor Astrobees positions

5. "Stop All" or "Terminate All" to stop/terminate all Astrobees

Or, each Astrobee can be stopped or terminated separately.

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Payload</th>
<th>Control</th>
<th>Operating State</th>
<th>Mobility State</th>
<th>Plan</th>
<th>Plan Status</th>
<th>Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astrobee 1</td>
<td>Error</td>
<td>Nominal</td>
<td>Guest Science</td>
<td>Free Flight</td>
<td>Test A-1</td>
<td>Running</td>
<td>50%</td>
</tr>
<tr>
<td>Astrobee 2</td>
<td></td>
<td></td>
<td>Guest Science</td>
<td></td>
<td>A-2</td>
<td>Running</td>
<td>75%</td>
</tr>
<tr>
<td>Astrobee 3</td>
<td></td>
<td></td>
<td>Guest Science</td>
<td></td>
<td>A-3</td>
<td>Running</td>
<td>25%</td>
</tr>
</tbody>
</table>
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