Rapid Development of the Seeker Free-Flying Inspector Guidance, Navigation, and Control System

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Overview

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- Seeker/Kenobi
- Linear Covariance Analysis
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- Summary

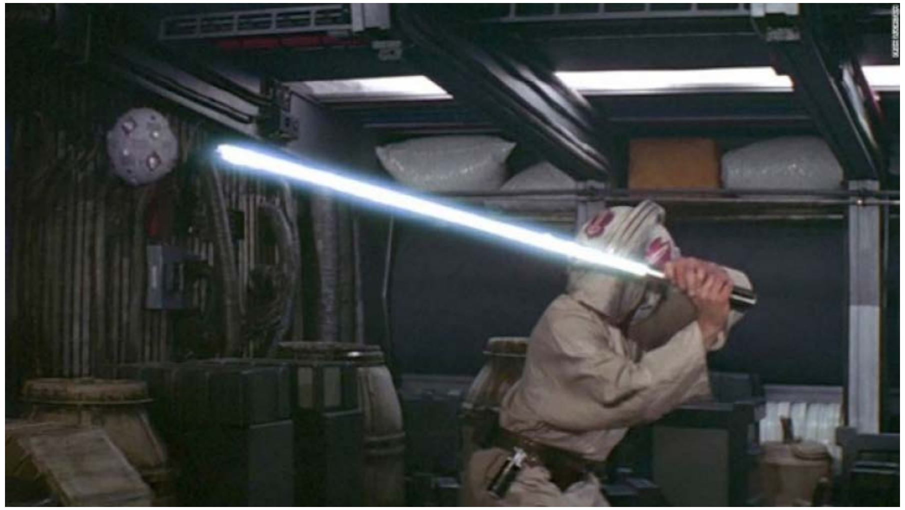
Free-Flying Inspector History

- **In-space inspection long-desired by NASA**
  - Damage Assessment
  - Periodic Inspection
  - External View of Critical Events
- **AERCam SPRINT**
  - Free-Flying Camera
  - Shuttle DTO for STS-87 (1997)
  - Teleoperated by Shuttle Astronauts
- **Mini AERCam**
  - Upgrade to AERCam SPRINT
  - Developed at JSC from 2000-2006
  - Significant upgrades to AERCam
    - Waypoint Guidance and Relative Navigation
    - Docking and Refueling Capability
    - Miniaturization of AERCam SPRINT
  - Never flown in space

Seeker and Kenobi

❑ Seeker: 3U Free-Flying CubeSat

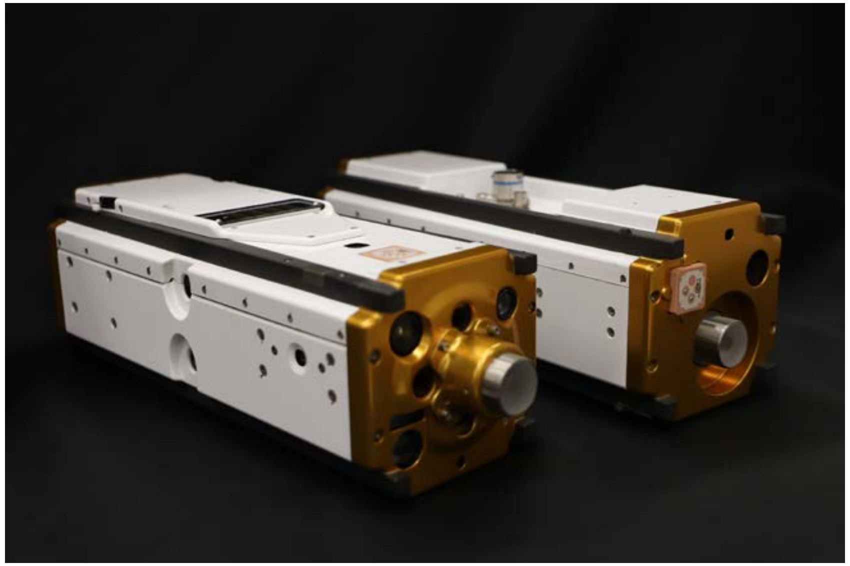
- Not an acronym (Jedi training droid)
- First step in development process
- Funded by ISS as “Class 1E” project
- Authority To Proceed: 07/26/2017
- Requested Delivery: 10/01/2018
- $1.8 million budget, 10 FTE allotted
- Early-career emphasis
- Launch aboard NG-11 in 2019
- 45 minute mission (lighting constraints)



Luke Skywalker training with Seeker Droid (Credit: Lucasfilm)

❑ Kenobi: Communication Box (3U Form Factor)

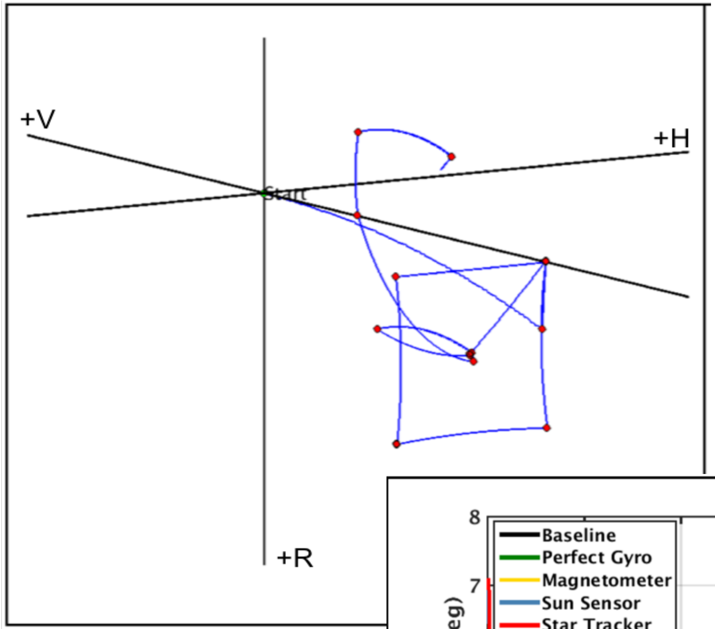
- Remains within NanoRacks deployer
- Communication and data storage
- Data telemetered down in weeks following mission

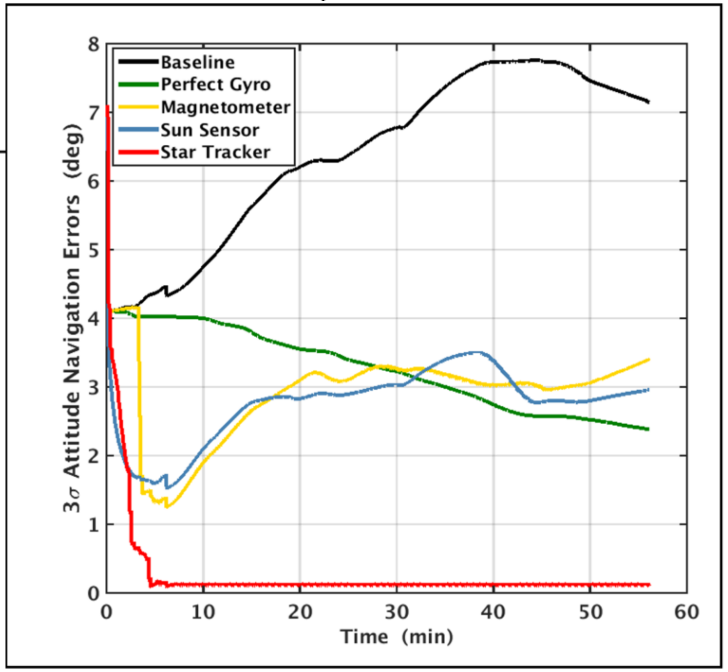


Seeker (left) and Kenobi (right)

Linear Covariance Analysis

- **Immediate need to determine sensor suite**
- **LinCov Analysis has long history at NASA**
  - Dating back to the Apollo Program
  - Similar statistics to Monte Carlo in single run
  - Rendezvous scenarios readily available
  - Quick iteration of system design
- **Converged on baseline sensor configuration**
  - IMU
  - Bearing sensor
  - Range sensor
  - Differenced GPS
- **Attitude error emerged as driving factor**
  - Evaluated star tracker, sun sensor, magnetometer
  - Price and lead time eliminated star tracker as option
  - Sun sensors added to baseline design

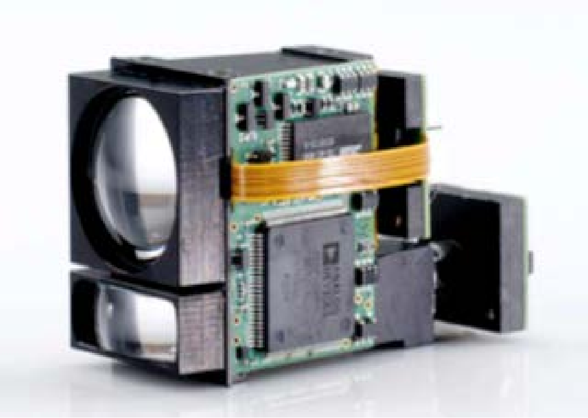




Sensor Downselection

- **Sensor selection based on cost, performance, lead time, and heritage (in that order)**
  - Space-rated items with flight heritage strongly preferred
  - If unavailable, consider tactical-grade units or units without heritage
- **IMU: Sensonor STIM 300-400-5**
  - Flight heritage with Raven (STP-H5)
  - Recommendation from GSFC Raven
- **Laser Rangefinder: Jenoptik DLEM-SR**
  - Tactical-grade rangefinder
  - Flight heritage with OCSD-A
- **GPS: SkyFox Labs piNAV-NG**
  - Flight heritage GPS receiver
  - TTFF from cold start: 90 seconds
- **Sun Sensors: SolarMEMS nanoSSOC-D60**
  - Selected based on unit cost and lead time
- **Bearing: Pursued camera-based approaches**
  - No LIDAR available meeting SWaP
  - Convolutional Neural Network (CNN) with UT-Austin
  - Scale-Invariant Feature Transform (SIFT) with local contractor

Sensonor STIM 300-400-5



Jenoptik DLEM-SR

SolarMEMS nanoSSOC-D60

Sensor Testing/Verification

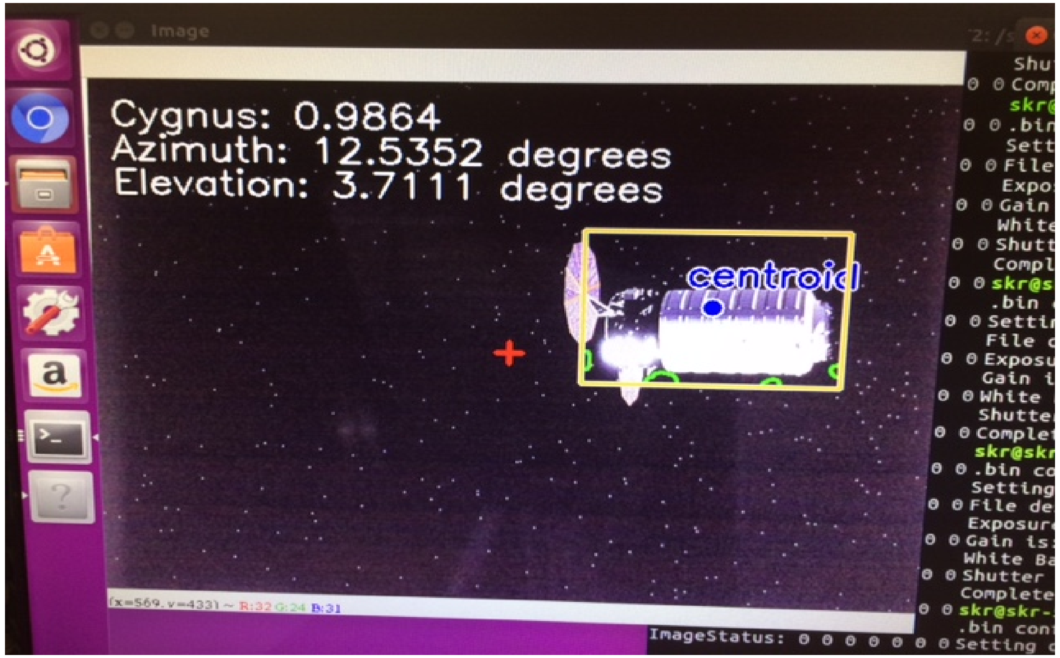
- Sensors tested for performance and survivability, not operability
- Space COTS sensors assumed to meet environmental specification
- Performed test series to attempt to qualify non-space rated sensors
  - Benchtop testing
  - Thermal (TestEquity Model 107)
    - Cycle between -44 C and +70 C
    - Operate at each temperature extreme
  - Vacuum (epoxy out-gassing vacuum chamber)
    - Re-test performance after 24 hours at -30 psig
  - Vibration
    - 9 GRMS random and sine, all axes
  - Blinding
    - All optics by pointing up on clear day
- LRF subject to range testing (with/without thermal)
- Sensors subjected to thermal, vacuum, EMI, vibe, shock on integrated vehicle

DLEM-SR Cold Extreme Thermal Testing

Laser Rangefinder Performance Testing at JSC Antenna Range

Visual Navigation (VizNav)

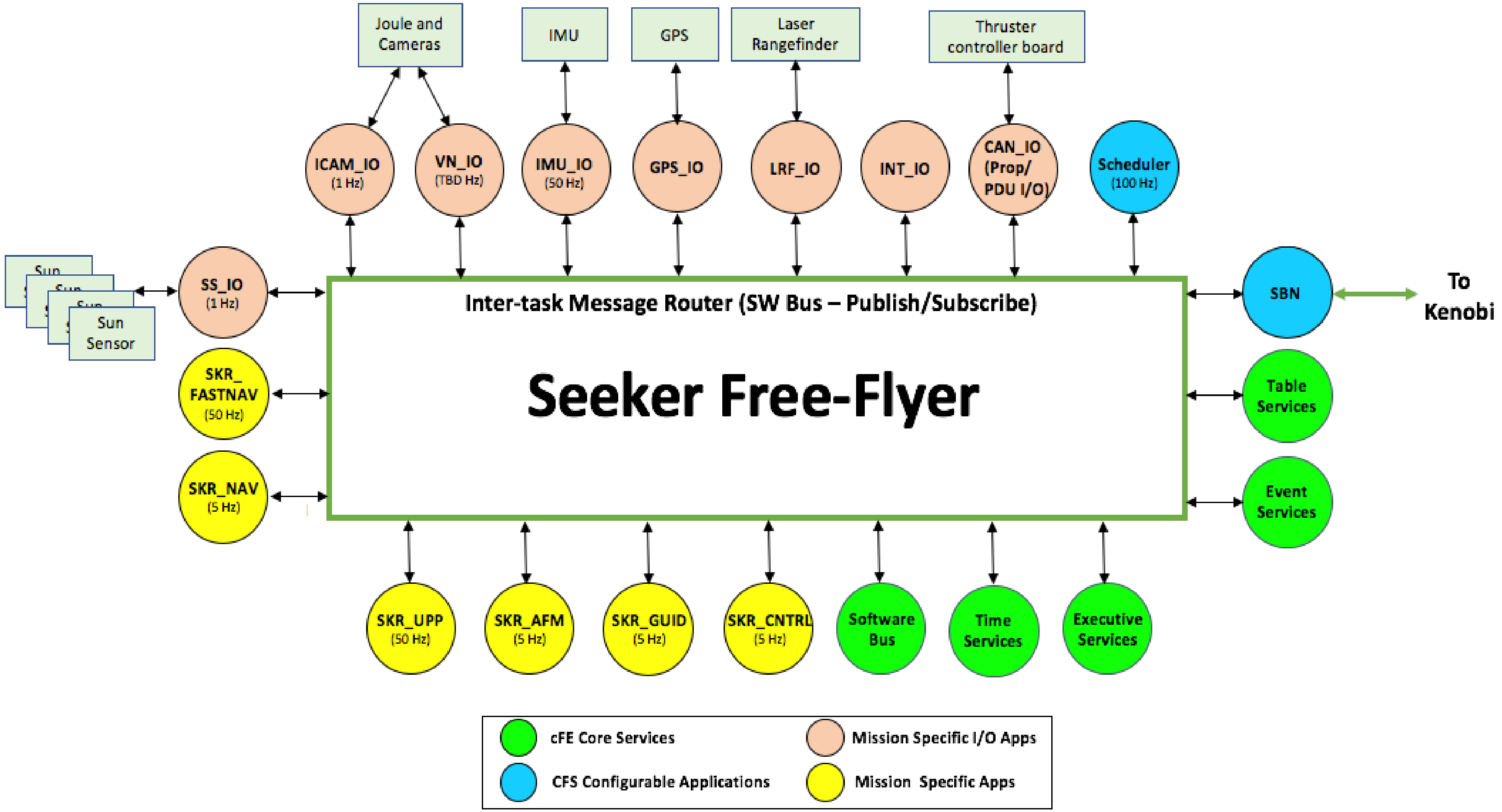
- **Three approaches pursued in parallel**
  - Neural Network (JSC internal)
  - Neural Network with Contouring (UT-Austin)
  - Scale-Invariant Feature Transform (Contractor)
- **Latter two approaches delivered mid-CY2018 for integration with Seeker FSW**
- **Both algorithms evaluated using 4K monitor in Seeker lab**
  - Similar to Orion optical navigation evaluation
  - Tested against Cygnus and non-Cygnus targets
- **UT-Austin approach selected**
  - More robust acquisition of target
  - Uncertain flight imagery
  - SIFT very sensitive to features



UT-Austin CNN Performance Evaluation in Seeker Lab

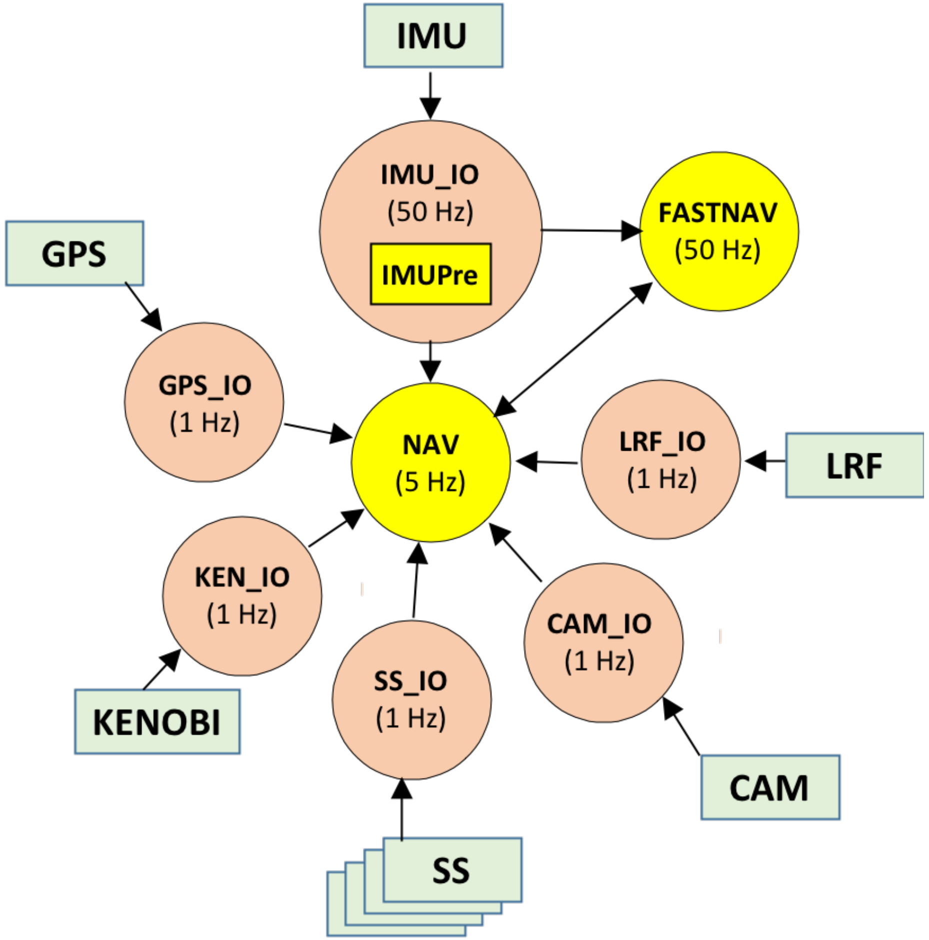
Core Flight Software Architecture

- CFS has long flight heritage, developed by GSFC
- Publish/Subscribe architecture, common template for app developers



Seeker Navigation Subsystem

- **Initially began parallel development of two architectures**
  - Purely kinematic (Relative state, Clohessey-Wiltsire dynamics)
  - Inertial navigation filter (Dual-Inertial or Inertial Relative)
- **Inertial-Relative Filter chosen after HSI-1**
  - Needed inertial frame to compensate for gyro drift
  - Inertial-Relative form simplifies measurement modeling
- **Navigation broken into three components**
- **IMU Preprocessor (IMUPre)**
  - Downsample IMU data to single 50Hz packet
  - Perform coning/sculling correction
- **FASTNAV**
  - Perform state integration using IMU data
  - Generate dynamics partials and State Transition Matrix
- **NAV**
  - Multiplicative Extended Kalman Filter (MEKF)
  - Perform measurement updates



Seeker Guidance Subsystem

- **Initial approach involved potential field-based guidance algorithms**
- **Artificial potential field steers Seeker to waypoints and away from hazards**
- **Abandoned for point-to-point guidance algorithm**
  - Resource and timeline constraints
- **Commanded velocity always in direction of next waypoint**
  - Constant magnitude if greater than iLoaded “stopping distance”
  - Linearly decreasing as Seeker approaches waypoint
  - Effectively bounds Seeker kinetic energy
- **Both target track and waypoint logic implemented for attitude guidance**
  - Target track to keep navigation camera and rangefinder pointed at target
  - Waypoint commands to attitude specified by Automated Flight Manager (AFM)
- **Keep-Out-Zone logic implemented (Stretch Goal)**
  - Guidance ignores commands to enter or pass through hazardous area
  - Future missions could generate Keep-Out-Zones in realtime
- **Simplified approach resulted in rapid development and testing**
- **Approach general enough to return to field-based guidance without redesign**

Seeker Control Subsystem

- **PID controller designed to calculate thruster duty cycle**
  - Derivative term zeroed due to uncertain acceleration measurement
  - Integral term limited to prevent saturation
- **Phase-plane controller designed for attitude control**
- **Control parameters are inputs into the system and can vary by mission phase**
  - Control gains
  - Integral limit
  - Minimum firing time
  - Phase plane limits
  - Firing time increment
- **Both translational and rotational control algorithms implemented in Simulink**
  - Enabled rapid development and analysis while simulation was under development
- **Final tunings performed in flight software after integrated testing**

Automated Tuning and Analysis

- **Trick Monte Carlo capability became available late in the project (August 2018)**
- **Personnel and schedule constraints demanded automated approach**
  - Developed “Tuning Bulldozer” to help the process
  - Vary individual filter parameters across a range using Monte Carlo in automated way
  - Resulting output viewable using Koviz, a JSC plotting tool
  - Run about 100 values for a parameter within an hour
  - Enabled distributed simulation tuning runs
  - Quickly revealed trends, sensitive parameters, and initial starting values
- **Automated process produced initial guesses for manual tuning**
- **Monte Carlo runs analyzed using VERAS tool**
  - Load and parse data, compare to requirements, and generate PDF reports
  - Enabled more traditional tuning approach
  - Quickly trade navigation accuracy, mission time, and propellant usage
- **Converged on parameters which should provide robust performance while achieving minimum, full, and stretch project goals**

ROSIE

- Rendezvous Operation Sensor and Imagery Evaluator (ROSIE)
- Collaboration between EG (Flight Mechanics) and ER (Robotics/Software) in 2017
- Platform for relative navigation sensor and algorithm testing
  - Smaller scale, simulate relative motion, avoid pushing a cart
  - Provide 6-DOF motion
  - Support 12”x12”x18” payloads of up to 40 lbs
  - May be driven by scripts, hand controller or Trick simulation
- Ideal platform for Seeker testing
  - Prototype FlatSat can fit on motion platform
  - Quickly reconfigurable
  - Real or simulated sensors or effectors
  - Development of interface allows ROSIE to be driven by Trick sim
- Test anywhere with large, open space and flat floor
- Initial tests used scripted motion, moved to simulation base

ROSIE Robot in Building 9 at JSC

Hardware/Software Integration (HSI)

- **Series of HSI milestones set by project to accelerate development**
  - Forcing function for development schedule
  - Three planned, four completed
- **HSI-1 (February 2018)**
  - Basic AFM functionality, camera I/O, prop controller
  - Navigation propagation and flight control
- **HSI-2 (April 2018)**
  - Guidance, NAV, AFM development and integration
  - Sensor interfaces, ground commanding
- **HSI-2.5 (July 2018)**
  - Integrate all hardware sensors, additional software upgrades
  - VizNav not yet available
- **HSI-3 (September 2018)**
  - VizNav integration, filter tuning, flight config
- **Multiple benefits to HSI schedule**
  - Develop interfaces early in project
  - Periodic re-integration with hardware

Seeker FlatSat on ROSIE Platform for HSI-3

Summary Gantt Chart