Implementation and Evaluation of Model-based Health Assessment for Spacecraft Autonomy

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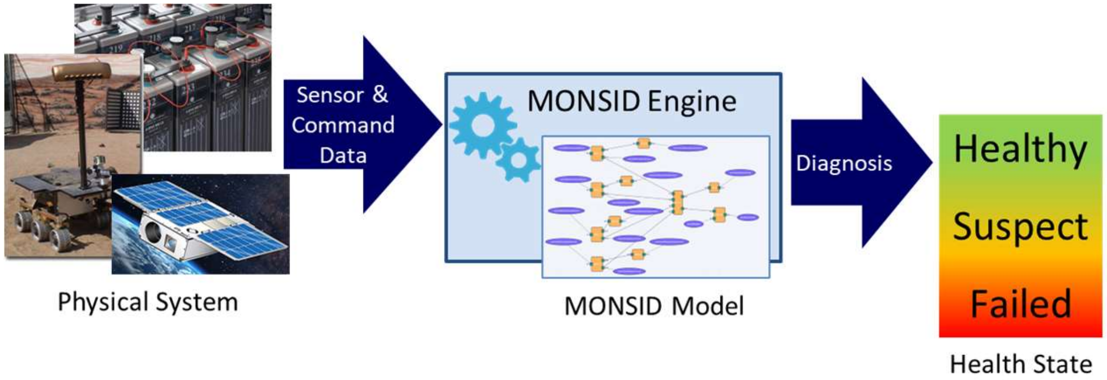
Agenda

- Introduction to Model-based Health Assessment
- The physical system and its model
- Test campaign and results
- Conclusions

Model-based Health Assessment

- Health assessment == health monitoring => fault management
- Model-based Off-Nominal State Identification and Detection (MONSID)
- Constraint suspension technique for fault identification
- Potential to detect unanticipated faults and off-nominal behavior



MONSID Heritage

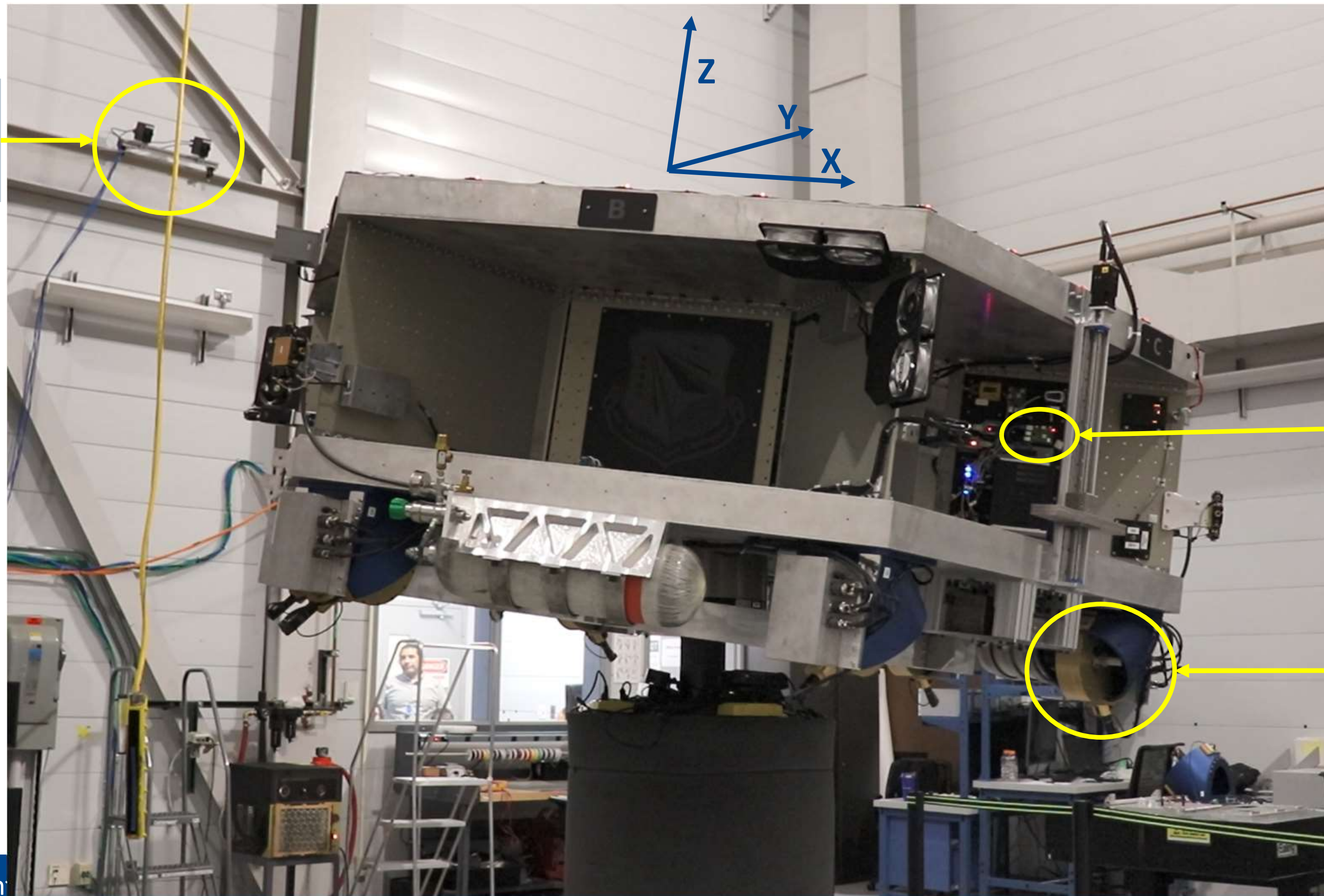
- Based on SBIR Phase I with AFRL (2013)
- MONSID C++ developed through SBIR I,II,II-x and III's with NASA (2015 – 2020)
  - JPL Test rover mobility system – uncovered firmware and FSW problems and detected real faults
  - ROS integration in state of the art 6-DOF Caltech CAST facility
  - Developed MONSID Toolkit visualization web app
  - Applied MONSID to propellant management systems (KSC)
- ASTERIA CubeSat extended mission (2020)
  - MONSID model of XACT ACS unit validated with flight data
  - Integrated with ASTERIA FSW (Fprime)
- Lunar Flashlight CubeSat I&T tool (2021-present)
  - Reused MONSID model of XACT ACS
- AFRL Phase II (2019-2021)
  - MONSID integration with cFS on 3-DOF ACS test bed
- NASA ROSES ColdTech award (2022-present)
  - 2-year subcontract to JPL to support robotic arm modeling and auto-recalibration of models

Physical System

AFRL Autonomy Testbed called BONSAI

Motion Capture
(MOCAP)
Cameras (16 total)

Not visible:
IMU
ACS processor



C&DH (Raspberry Pi)
MONSID

CMG (6 total)

BONSAI Implementation - I

Platform Characterization & Model development

- Platform Data
  - Gimbal angle commands, Hall, Encoder, IMU, MOCAP (attitude) available
  - Analogs and inner motor control loop data not available

- Modeled Components:
  - Gimbals
  - Gimbal Hall sensor (rate)
  - Encoder sensor (angle)
  - Rotor
  - IMU
  - MOCAP

BONSAI Implementation - 2

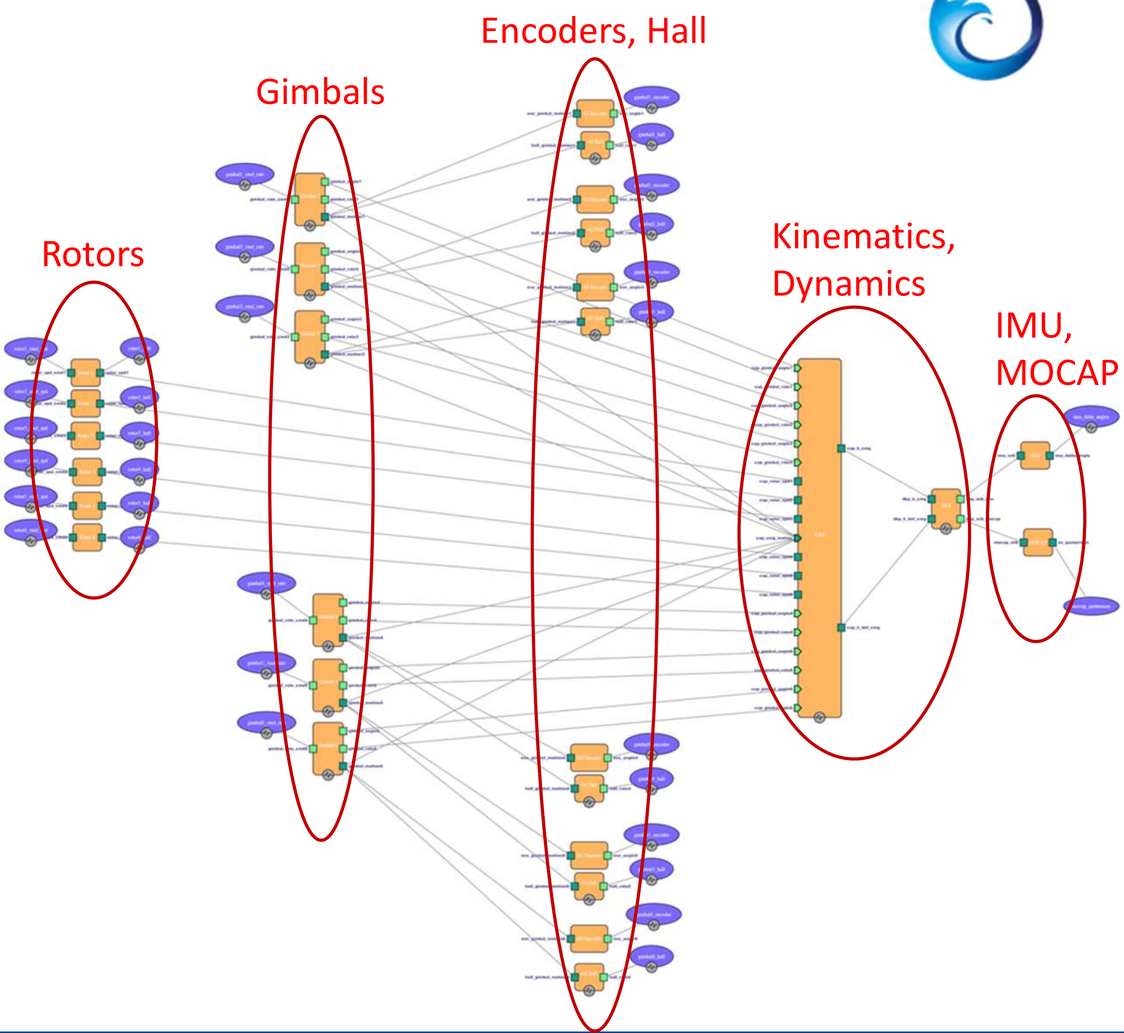
Platform Characterization & Model development

- Data Rates & Quality
  - Attitude Estimation runs at 100 Hz
  - 50 Hz (IMU) and 10 Hz (Controller) sampled and held
  - Hall and MOCAP data very noisy

- Data down sampled to 10 Hz
  - Reduced sample-hold effects
- Modeled simplified gimbal motion to mitigate effects of non-linearities
- Filtered MOCAP data prior to use in model

MONSID Model

- Intended to identify faults in individual CMG components
- Possible to distinguish among faults in gimbals, encoders, gimbal Halls, and rotors.
- Possible to distinguish IMU faults from MOCAP faults



Injected Faults

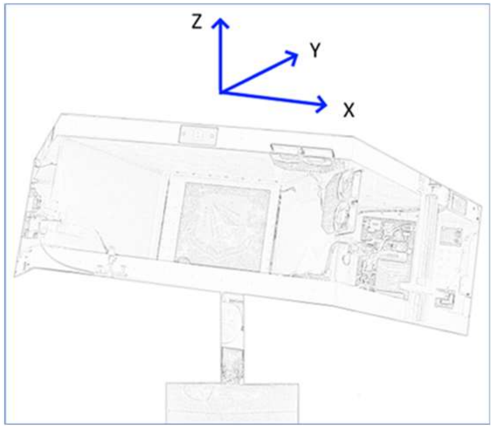
Safety First!

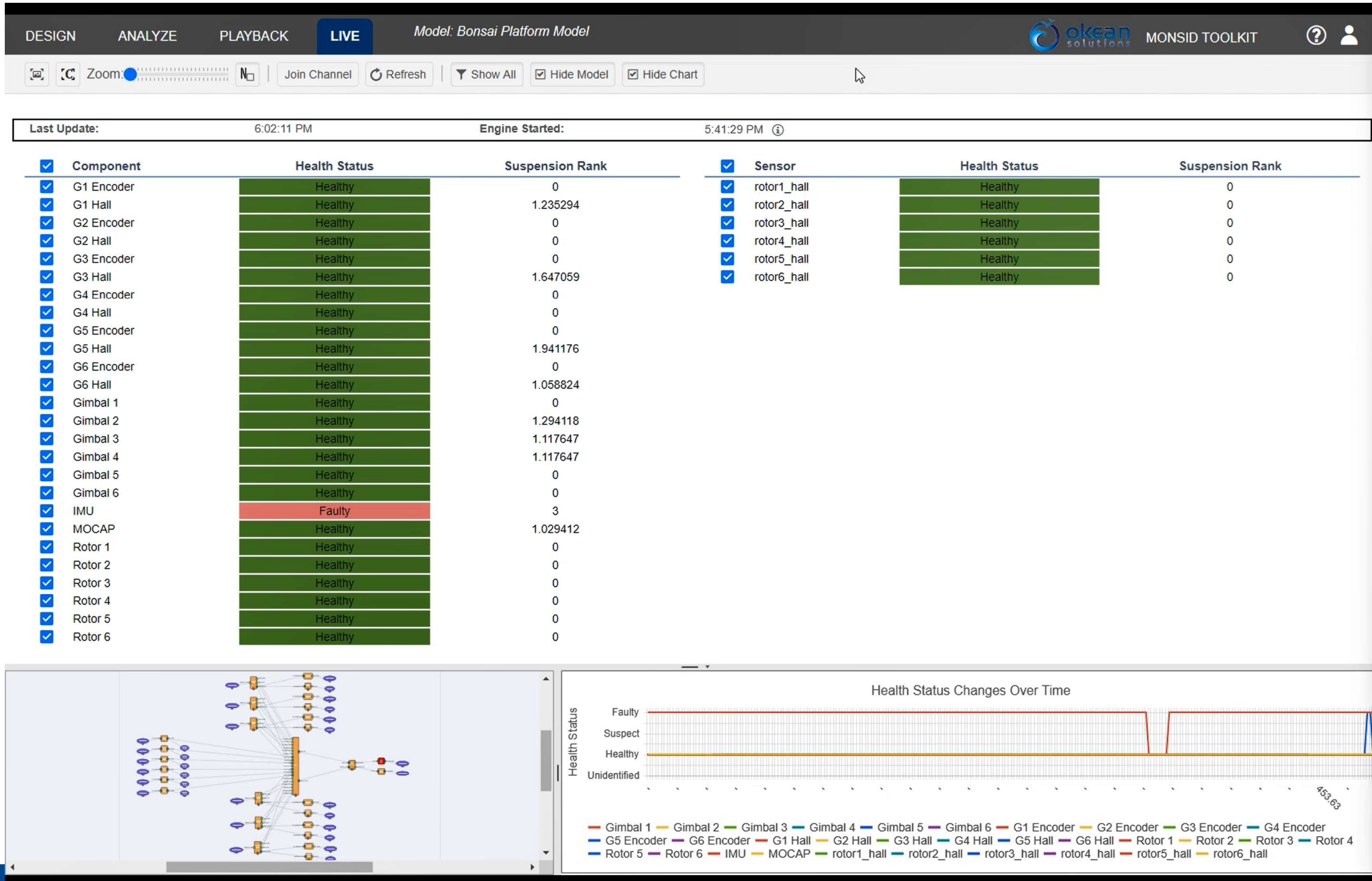
Fault	Injection Method
Gimbal fail to zero	Zero out gimbal rates, gimbal angles remain constant
Rotor fail to zero	Remove command to rotor loop only so rotor naturally spins down (non-zero commands still seen by MONSIDand ACS software)
Encoder fail to zero	Zero out encoder signal
IMU bias drift (z-axis)	Add bias acceleration to IMU signal on z-axis
IMU fail to zero (single axis)	Zero out IMU signal on specified axis (x or y only)

- Single faults
- Double faults occurring simultaneously
  - Rotor and IMU
  - Rotor and encoder
  - Rotor and gimbal Hall

Test Campaign

- Designed to represent realistic spacecraft maneuvers
- 5 different slew profiles used in nominal and fault scenarios
  - Per-axis slews
  - Slews between 2 fixed attitudes
  - Spiral scan composed of body y and z-axis slews
  - Constant and sinusoidal tracking slews about z-axis
- 3-9 minutes in duration to avoid saturating the gimbals
- Planned 42 total runs consisting of:
  - Nominal
  - Single injected faults
  - Double injected faults




DESIGN
ANALYZE
PLAYBACK
LIVE
Model: Bonsai Platform Model
okean solutions
MONSID TOOLKIT
Zoom:
Join Channel
Refresh
Show All
Hide Model
Hide Chart
Last Update: 6:02:11 PM
Engine Started: 5:41:29 PM
Component | Health Status | Suspension Rank
G1 Encoder | Healthy | 0
G1 Hall | Healthy | 1.235294
G2 Encoder | Healthy | 0
G2 Hall | Healthy | 0
G3 Encoder | Healthy | 0
G3 Hall | Healthy | 1.647059
G4 Encoder | Healthy | 0
G4 Hall | Healthy | 0
G5 Encoder | Healthy | 0
G5 Hall | Healthy | 1.941176
G6 Encoder | Healthy | 0
G6 Hall | Healthy | 1.058824
Gimbal 1 | Healthy | 0
Gimbal 2 | Healthy | 1.294118
Gimbal 3 | Healthy | 1.117647
Gimbal 4 | Healthy | 1.117647
Gimbal 5 | Healthy | 0
Gimbal 6 | Healthy | 0
IMU | Faulty | 3
MOCAP | Healthy | 1.029412
Rotor 1 | Healthy | 0
Rotor 2 | Healthy | 0
Rotor 3 | Healthy | 0
Rotor 4 | Healthy | 0
Rotor 5 | Healthy | 0
Rotor 6 | Healthy | 0
Sensor | Health Status | Suspension Rank
rotor1_hall | Healthy | 0
rotor2_hall | Healthy | 0
rotor3_hall | Healthy | 0
rotor4_hall | Healthy | 0
rotor5_hall | Healthy | 0
rotor6_hall | Healthy | 0
Health Status Changes Over Time
Health Status
Faulty
Suspect
Healthy
Unidentified
453.63
Gimbal 1 Gimbal 2 Gimbal 3 Gimbal 4 Gimbal 5 Gimbal 6 G1 Encoder G2 Encoder G3 Encoder G4 Encoder
G5 Encoder G6 Encoder G1 Hall G2 Hall G3 Hall G4 Hall G5 Hall G6 Hall Rotor 1 Rotor 2 Rotor 3 Rotor 4
Rotor 5 Rotor 6 IMU MOCAP rotor1_hall rotor2_hall rotor3_hall rotor4_hall rotor5_hall rotor6_hall

Interesting Cases

Unanticipated, previously unknown behaviors

- Gimbal Hall sensor anomalies
  - During quiescent periods, sensor data sometimes latched to a constant value just outside the deadband
  - During slow movement, sensors sometimes latched to a value inside the deadband
  - MONSID detected this behavior and correctly attributed to gimbal Hall sensors
- Unresponsive gimbals -> actual hardware fault!
  - Individual gimbals would simply stop responding to commands
  - Occurred singly and in pairs (double fault condition)
  - MONSID correctly identified the unresponsive gimbals and verified that encoders and Hall sensors were healthy
  - Operators never before noticed this!

Performance Metrics

- False positive (FP): incorrect detection of a fault when the system is operating nominally
- True diagnosis (TD): correct diagnosis of true faults
  - Similar to *true positive* but includes true detection and correct identification of the faulty items
- Mis-diagnosis (MD): an incorrect diagnosis of true faults
  - True faulty items were not in the list of identified faulty items

Results Summary

- 10 nominal runs:
  - FP rates: 1.4% to 0.01%
  - Most FP due to gimbal Hall sensor anomalies
- 11 injected fault runs:
  - FP rates < 1%
  - TD rates 95% to 100%, one outlier with 89%
  - MD rates 5% to 0%, one outlier with 11%
- 13 runs had unanticipated, concurrent real gimbal faults
  - 10 intended nominal runs
  - 3 injected fault runs
- 3 of the IMU single axis fail to zero cases did not perform well due to instabilities and incorrect fault injection
- 5 runs were eliminated due to instabilities

Improvement Ideas

- Gimbal faults reliably detected only when gimbals were commanded to move
- Addition of motor voltage or current data could be incorporated into the model to detect some faults even when the gimbals were not moving
- The addition of such signals could potentially improve fault identification performance as well
- Improve tuning to decrease MD rates
- Increase sensitivity to IMU faults

Conclusions

- Correctly diagnosed injected CMG and IMU faults
- Cases of transient hall sensor latching were also detected
- Detected real gimbal hardware faults
- MONSID has shown its ability to detect and identify multiple simultaneously occurring faults

Acknowledgments

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