Spacecraft Autonomy Experiments Using the MIT SPHERES on the ISS

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MIT SSL

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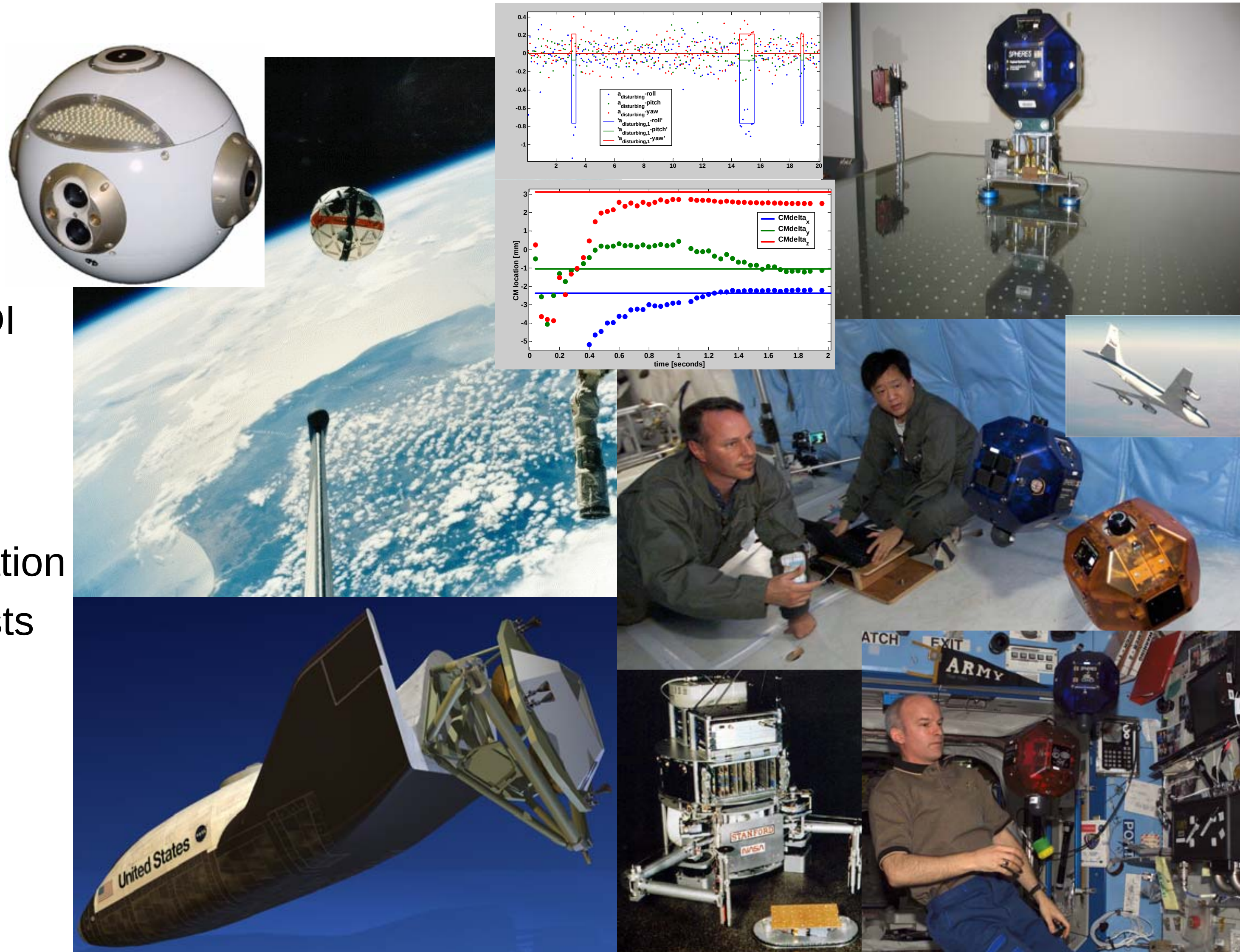
NASA

Research objective: For thruster-controlled spacecraft, develop, implement, and test technologies that use existing navigation sensors (gyros, optionally accels) to increase spacecraft autonomy: **On-line thruster fault tolerance**; **estimation of mass- and thruster-properties**.

Outline:

- SC Autonomy
  - Thruster FDI
  - Mass ID
  - X-38 Sim
- SPHERES
  - Implementation
  - Air table tests
  - KC 135
  - ISS



Spacecraft autonomy

- What does it mean? Many different levels:
  - General: e.g., Deep Space 1 / Remote Agent
  - Mission specific: Autonomous docking (vs. automated)
  - Operational: Crew can operate autonomous from ground control
- Balance between complexity, accuracy, robustness.
- Mission-related factors – safe mode available?
- Specific or general (e.g., model entire system, with autonomous planner to meet objectives).
- Can be an enabling information technology by reducing hardware redundancy requirements.

X-38

- Test vehicle for Crew Return Vehicle (both cancelled)
- Requirement for thruster FDI during de-orbit phase, no pressure sensors available.
- Project with NASA JSC provided focus that drove development of these SC autonomy technologies

Motion-based Thruster Fault Detection and Isolation (FDI)

- Problem statement:
  - For a thruster-controlled spacecraft, with realistic thrust variability, using gyros only, accels if available
  - Detect and isolate thruster faults: Single- and multiple-jet; abrupt; hard; failed-on or failed-off; for X-38, DPS RCS and Axial
  - Feasible for present-day implementation. Broad applicability important.
- Principal challenges:
  - Low SNR due to thruster variability, sensor noise, poorly characterized vehicle model, disturbances
  - Optimizing response time while maintaining high accuracy
  - Balance risk of false positive vs. missed detection
  - Limited thruster excitation permitted – to exonerate alias faults
  - Compared with existing body of FDI, presence of on/off actuators a problem
  - Model-based, but with minimal sensing
- Sensor-based FDI uses temperature, pressure, electrical sensors – increased mass, cost, complexity
- Motion-based FDI most applicable for autonomous, maneuvering spacecraft (vs. human-rated)
- FDI ➔ R by switching to backup or reconfiguring control
- Related Research:
  - Deyst and Deckert (1976) – Maximum likelihood thruster FDI
  - Wilson and Rock (1994) – RLS combined thruster/mass ID
  - Lee (1999) – Cassini leak detector, Kalman filter

Thruster FDI approaches

- Recursive Least Squares (RLS) – Simultaneously ID all thruster strengths, declare detection when out of spec.
- Targeted RLS – One RLS process running for each thruster.
- Bank of Kalman Filters – One (steady state) KF running for each fault mode, examine residuals.
- Maximum Likelihood – Determine the fault mode whose resulting accelerations most closely match the measured angular accelerations
- Difficulties presented by low SNR and biases – exceptionally challenging for X-38. All other vehicles relatively straightforward after X-38 was solved: Mini-AERCam, S4, SPHERES, CEV re-entry.

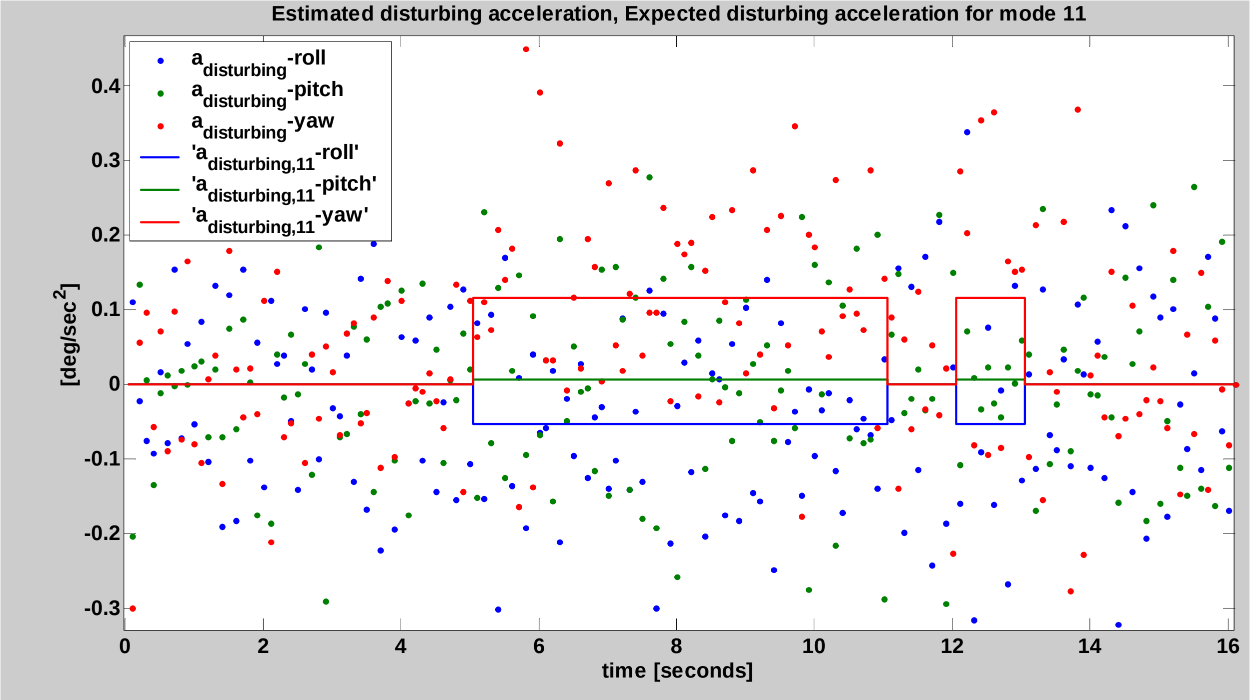
Maximum Likelihood FDI

- Challenge is optimizing response time while maintaining accuracy.

- Algorithm’s **core** based on a 1976 paper by Deyst and Deckert on leak detection for the Space Shuttle Orbiter (MIT / Draper Lab)
- Calculates difference between expected and actual angular acceleration
- Compares this “disturbing acceleration” to that corresponding to the possible failure modes
- Due to low SNR and failure modes with similar disturbing accelerations, **filtering and windowing** data required
- Detection based upon generalized likelihood ratio (GLR) test for each failure mode
- Isolation based on the likelihood calculation for each failure mode
- Excitation of thrusters required in some cases
- **Logic** to disregard some failures, select correct failure mode

X-38 Sim Results

Example of low SNR ➔ challenging FDI for X-38

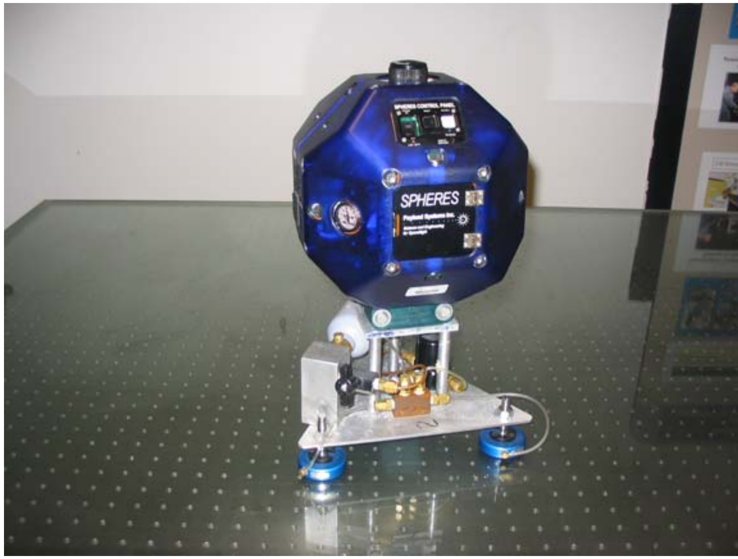


- Detection within 1 second (active time) for X-38
- Isolation within 1-5 seconds for X-38
- Extended testing run for X-38 – **99.9994%** accurate FDI
- FDI developed on X-38, then easily “ported” to Mini-AERCam, S4, SPHERES, CEV re-entry.

Motion-based mass-property ID

- Problem statement:
  - For a thruster-controlled spacecraft, using gyros only
  - ID mass center, inertia matrix, thruster force magnitude
- Why?
  - Mass properties often surprisingly difficult to determine before flight (from ground measurement or CAD). Change after launch – fuel, reconfiguration, payload change.
  - Small disturbances in space ➔ motion-based (**gyros** are sufficient) analysis is possible, and often more accurate than ground testing
  - Mass properties can significantly impact advanced control, estimation, and FDI calculations. Mir-Progress docking accident.
- Principal challenge:
  - Unknown parameters (CM, I) do not appear linearly in the equations of motion ➔ direct Least Squares (LS) solution not possible
- Related Research:
  - Tanygin and Williams (1997) – spinning, coasting, LS
  - Bergmann *et al* (1987) – Kalman filter
  - Wilson and Rock (1994) – RLS combined thruster/mass ID; used for on-line neural-network control reconfiguration following multiple thruster failures

SPHERES Overview

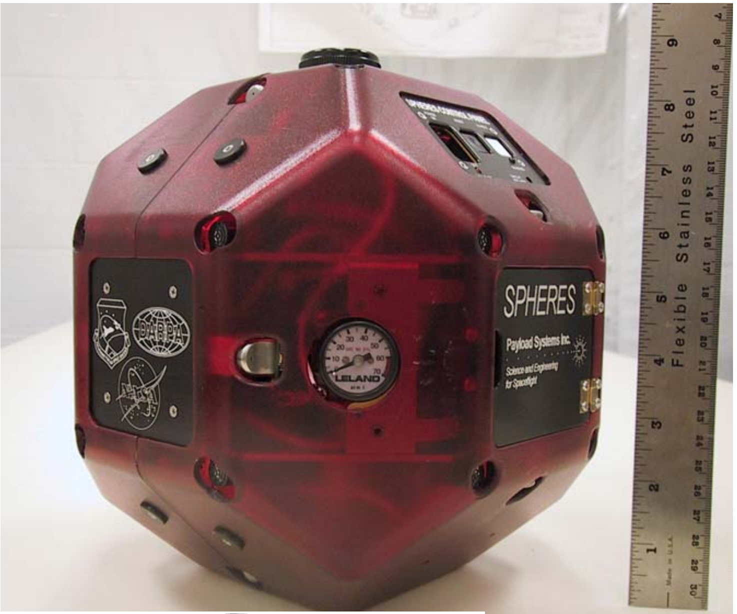


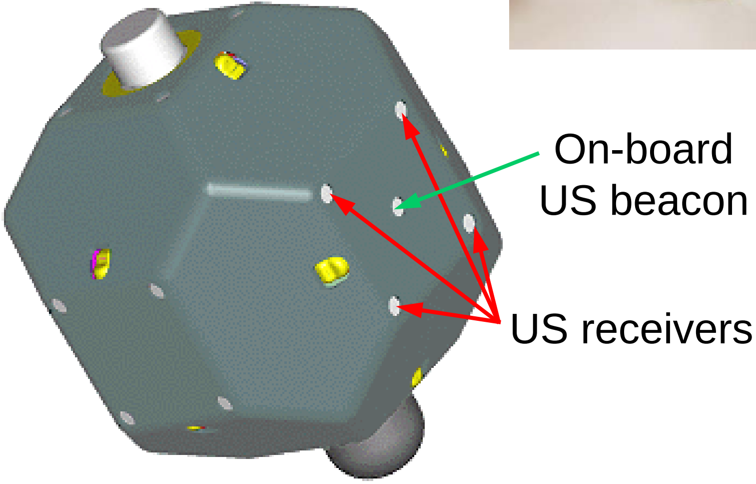
- Synchronized Position Hold Engage Reorient Experimental Satellites
- MIT Space Systems Lab / Payload Systems Inc.
- SPHERES is a cost-effective, risk-tolerant, **interactive testbed** operated inside the ISS for the development and maturation of formation flight and autonomous rendezvous and docking technologies (autonomy, control, and metrology).
- Safety certified, operating inside ISS with iterative experimentation enables rapid development and test of advanced information technologies.

- Multi-vehicle Testbed - long duration micro-gravity environment allows 6DOF per vehicle and close proximity maneuvers representative of envisioned missions: TPF, Starlight, TechSat 21, Orbital Express, and Mars Sample Return.
- Cost-effective - replenishable consumables, IFM and observations by crew reduce operation costs; data (up)downlink and video coverage expedites algorithm design; reconfigurable and upgradeable hardware accommodates new technologies.
- Risk-tolerant - ill-behaved algorithms can be stopped and corrected without affecting future operations. Allows software to mature from conception to flight quality without danger of mission failure.

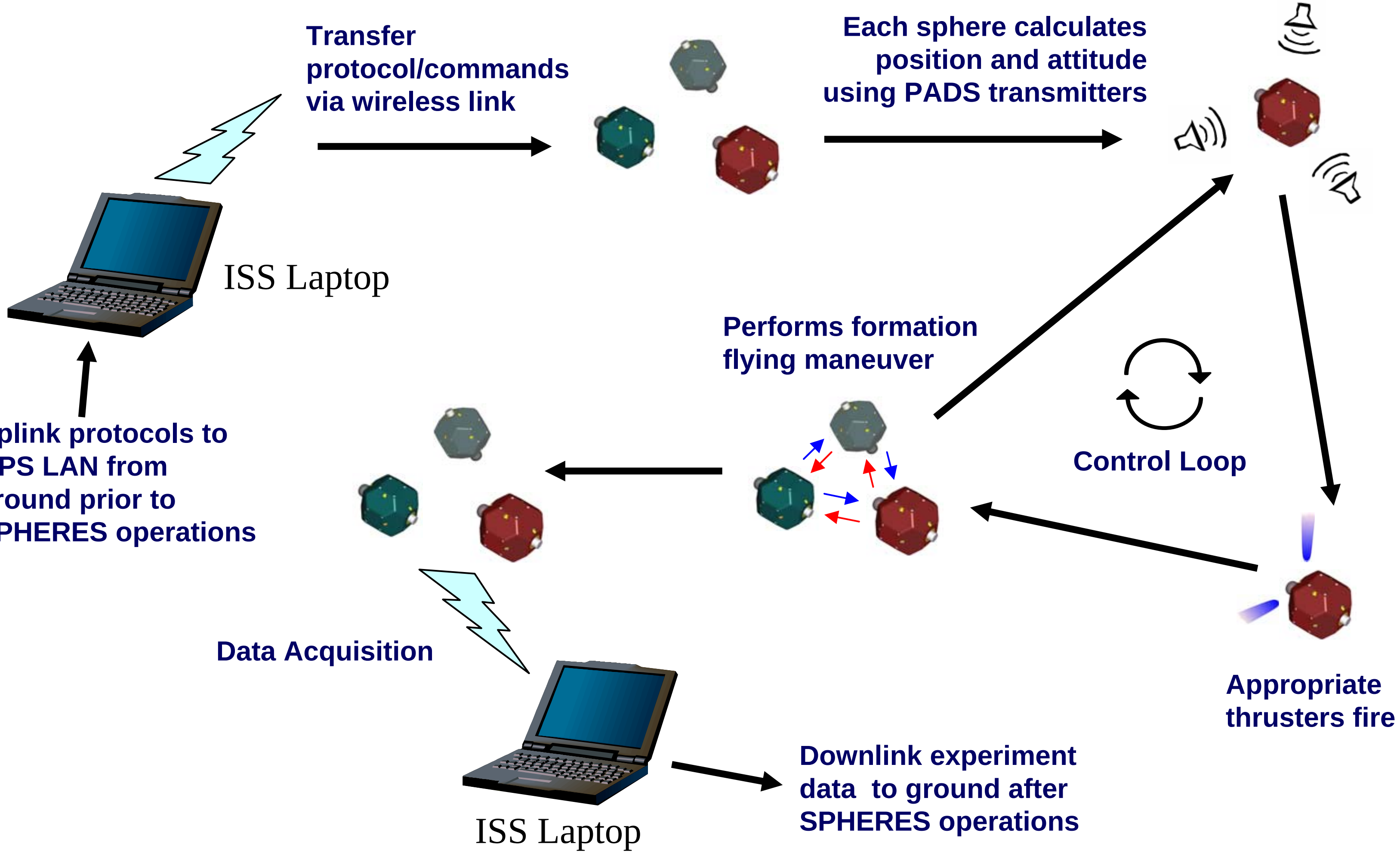
SPHERES properties

- Thruster propelled – 12 thrusters / 6 dof
- 0.1 N thrust, 10 ms minimum firing time
- Liquid CO2 propellant – 860 psi / 35 psi regulated
- 21 cm diameter
- 4.4 kg mass with full CO2 tank
- Replenishable tanks/AA batteries
- Gyros, accelerometers, Ultrasound-based position and attitude determination
- TI TMS320C6701 floating point DSP, Sundance SMT375 board
- FDI, mass ID algorithms implemented in C / Embedded C++
- 10 Hz control update, 1 kHz gyro sampling
- 1-3 spacecraft depending on experiment
- RF communication: SPHERES-SPHERES and SPHERES-laptop
- Multiple ~2-hour experiment sessions enable ***experimental iteration***. Astronaut supervised, interior to ISS.





Typical Test Session Flowchart



Uplink protocols to OPS LAN from ground prior to SPHERES operations

ISS Laptop

Transfer protocol/commands via wireless link

Each sphere calculates position and attitude using PADS transmitters

Appropriate thrusters fire

Control Loop

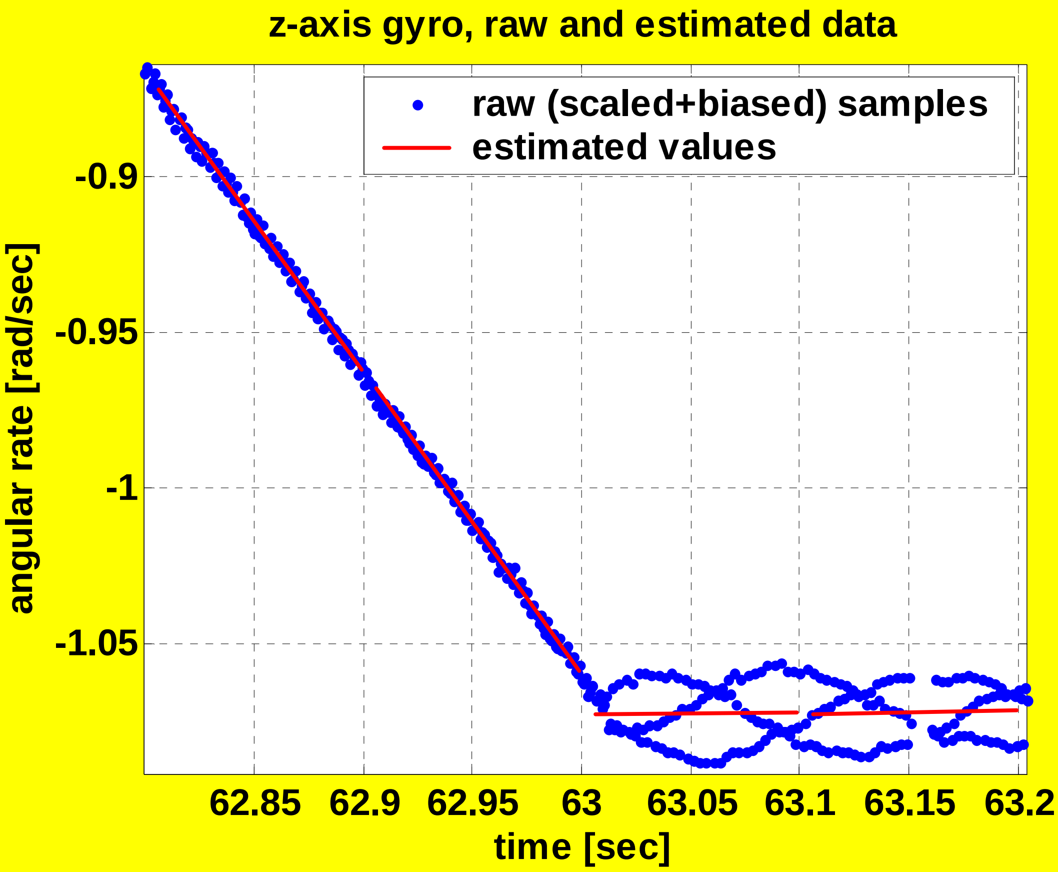
Performs formation flying maneuver

Data Acquisition

ISS Laptop

Downlink experiment data to ground after SPHERES operations

Acceleration estimation



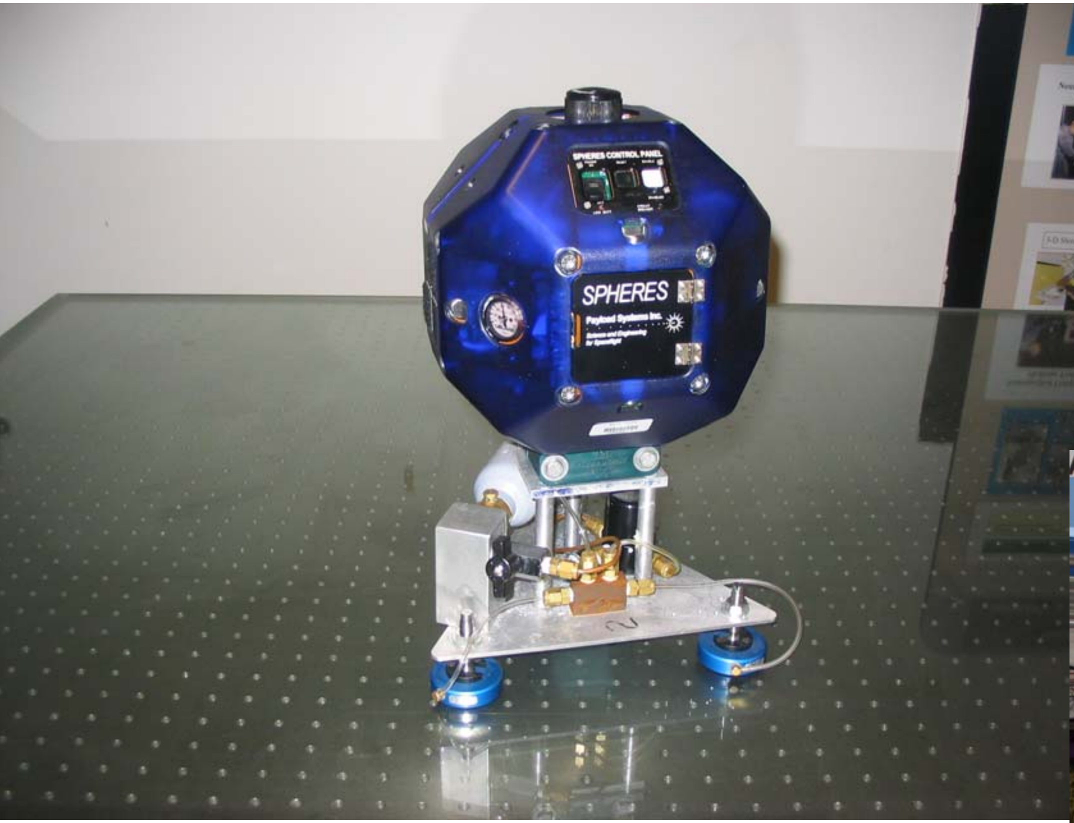
Estimated segment accelerations:
-0.9665 -0.9773 0.0133 0.0167

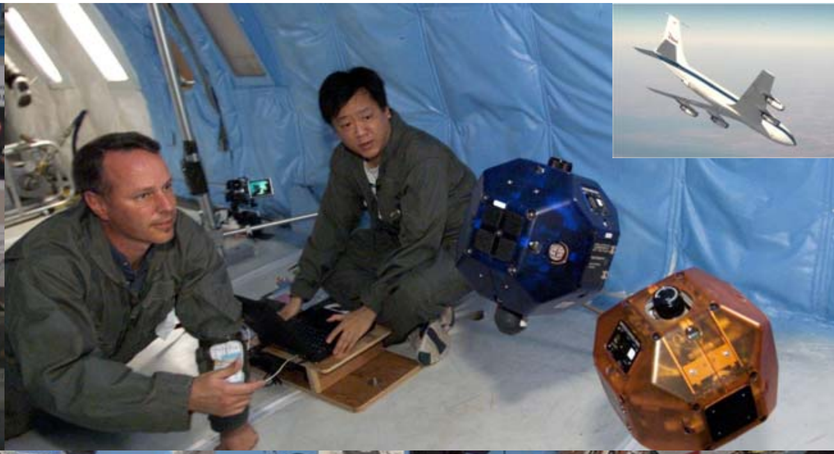
- Accurate acceleration estimation is critical to FDI and ID
- In general can be derived from other sensors (star tracker, video sensor, etc.). Gyros+accels used here.
- Inertial sensors generally susceptible to vibrations – ringing here for the BEI Gyrochip II tuning fork rate sensor
- Accurate estimation based on data from each control segment, causal, efficiently implemented, zero lag, accounts for thruster latency
- This data from KC-135 tests

Simplified FDI algorithm

- For many spacecraft, the windowing aspect of the algorithm is not needed.
- Simplified version implemented in flight code:
  - 24 thruster accelerations (also fault signatures) pre-calculated – 6x24 matrix, automatically generated C code based on vehicle properties
  - Multi-jet thrust scale factors calculated
  - Disturbing acceleration calculated from filtered sensors and nominal acceleration
  - Likelihood parameters (lambdas) calculated for each fault, using 6x24 matrix, disturbing acceleration
  - Disturbance detector – must match at least one of 24 or case of no faults
  - Detection based on generalized likelihood ratio test
  - List of candidates initialized ➔ active during detection
  - Candidates exonerated based on lambda active or inactive
  - Immediately down to 2 or 4 candidates on detection step (aliases)
  - Automatic excitation finalizes isolation in one or two cycles
  - Switch in reconfigured controller

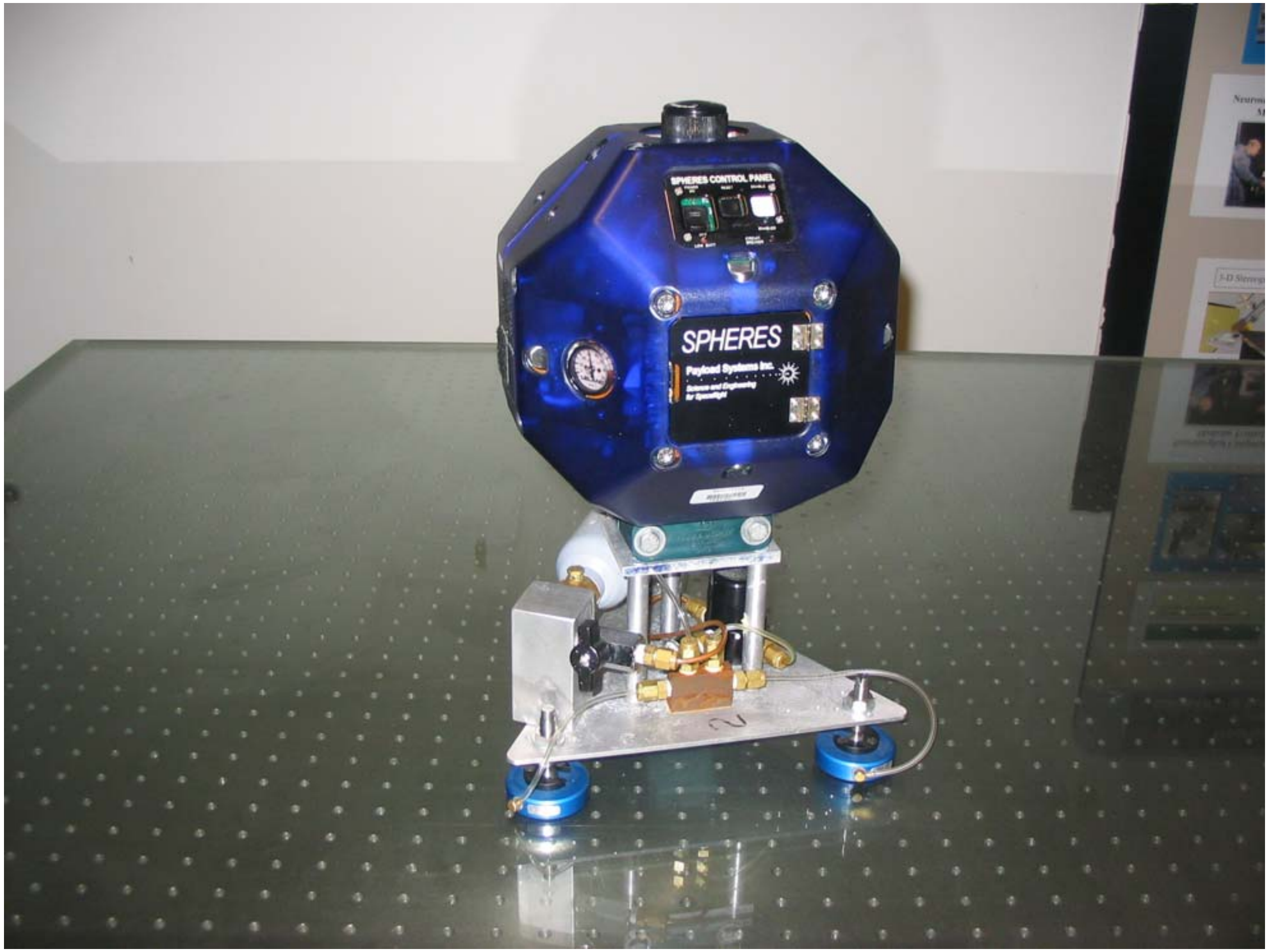
SPHERES test environments





- 1-g Air-bearing supported
- KC-135 0-g parabolas
- ISS

Air bearing, Thruster FDIR

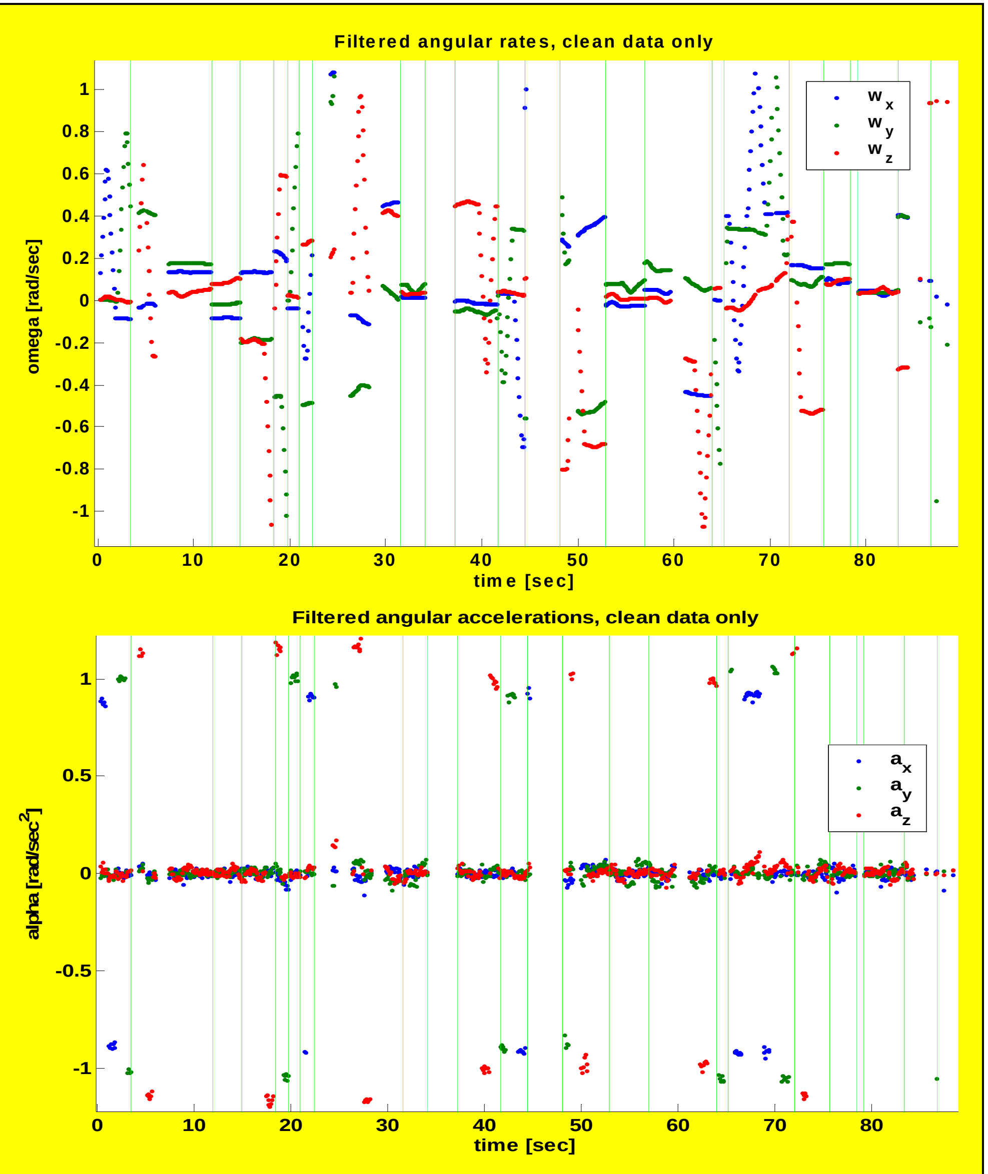


- FDIR to a failed-off thruster. 2-D, 4 thrusters used. One failed (in software).

KC-135 testing

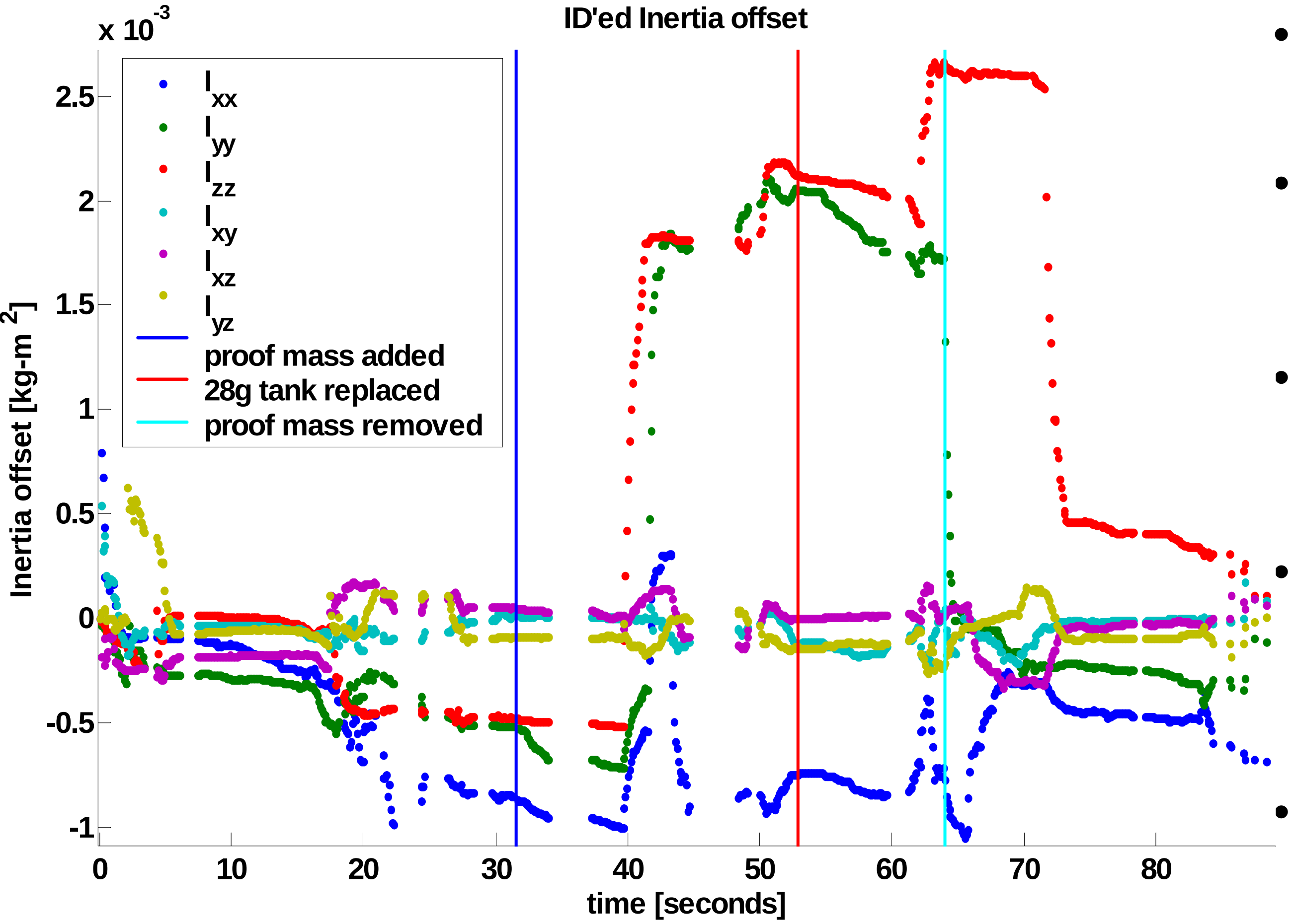
- Brief periods of 0-g. Splice together to get data needed.

KC-135 data: omega, alpha



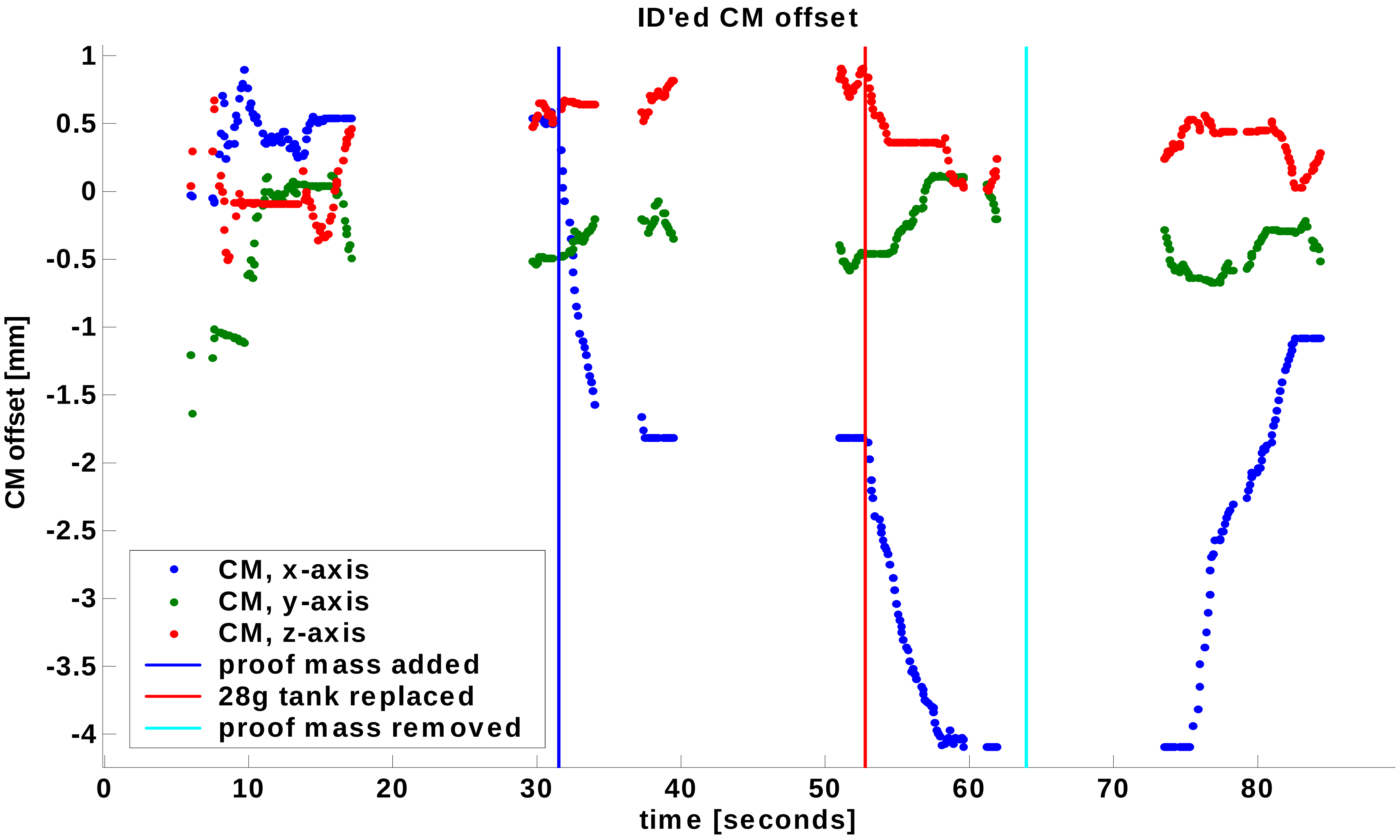
- Controller runs at 10 Hz, gyros sampled at 1 kHz
- Omega, alpha filtered on-board for every 100 ms control segment
- Telemetered for post-flight analysis
- Since for FDI and ID, desire to correlate alpha to thrusters for each segment.
- Failures may occur at any time ➔ filtering cannot assume thruster knowledge
- Alpha data shows pure rotations, pure translations, gyroscopic effects

KC data: Inertia ID



- Proof mass added, removed, near-empty tank replaced
- Fast response indicates feasibility for spacecraft with variable payload or internal reconfiguration
- Certain sections off apparent convergence are actually periods of little excitation
- Meaningful numerical results will require more data, resolution of remaining thruster characterization issues
- So far, effect of fuel slosh appears minimal – as hoped, it averages out and does not impact the ID results

KC data: CM ID


ID'ed CM offset
CM offset [mm]
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
0
10
20
30
40
50
60
70
80
time [seconds]
● CM, x-axis
● CM, y-axis
● CM, z-axis
proof mass added
28g tank replaced
proof mass removed

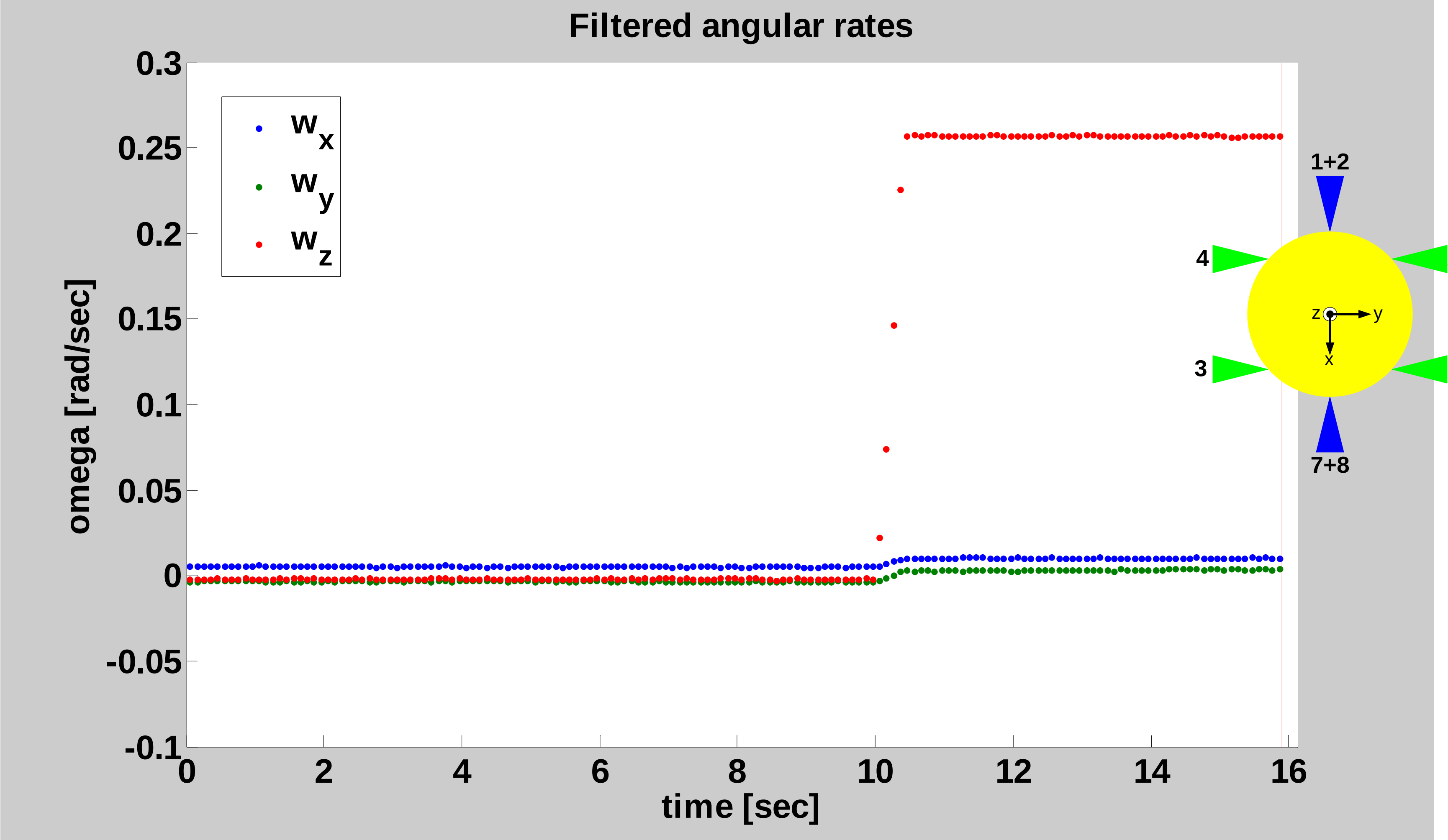
ISS Testing - FDI

- May 20, 2006. SPHERES TS2.
- Crew: Jeff Williams
- Example instructions:
  - **Title:**
  - Failed-on thruster FDI
  - **Objective:**
  - Automatically detect a simulated failed-on thruster.
  - **Approximate Run Time:**
  - Dynamic phase: 15 seconds
  - The test terminates automatically.
  - **Test Synopsis:**
  - The test starts with no firings. After 10 seconds a thruster turns on to simulate a failure. The FDI algorithm should detect this in less than one second and shut the thruster off.
  - ***Note:*** *if the thruster is on for more than one second end the test manually using the GUI Stop button.*
  - **Nonstandard Initial Conditions:**
  - None, follow the prompts.

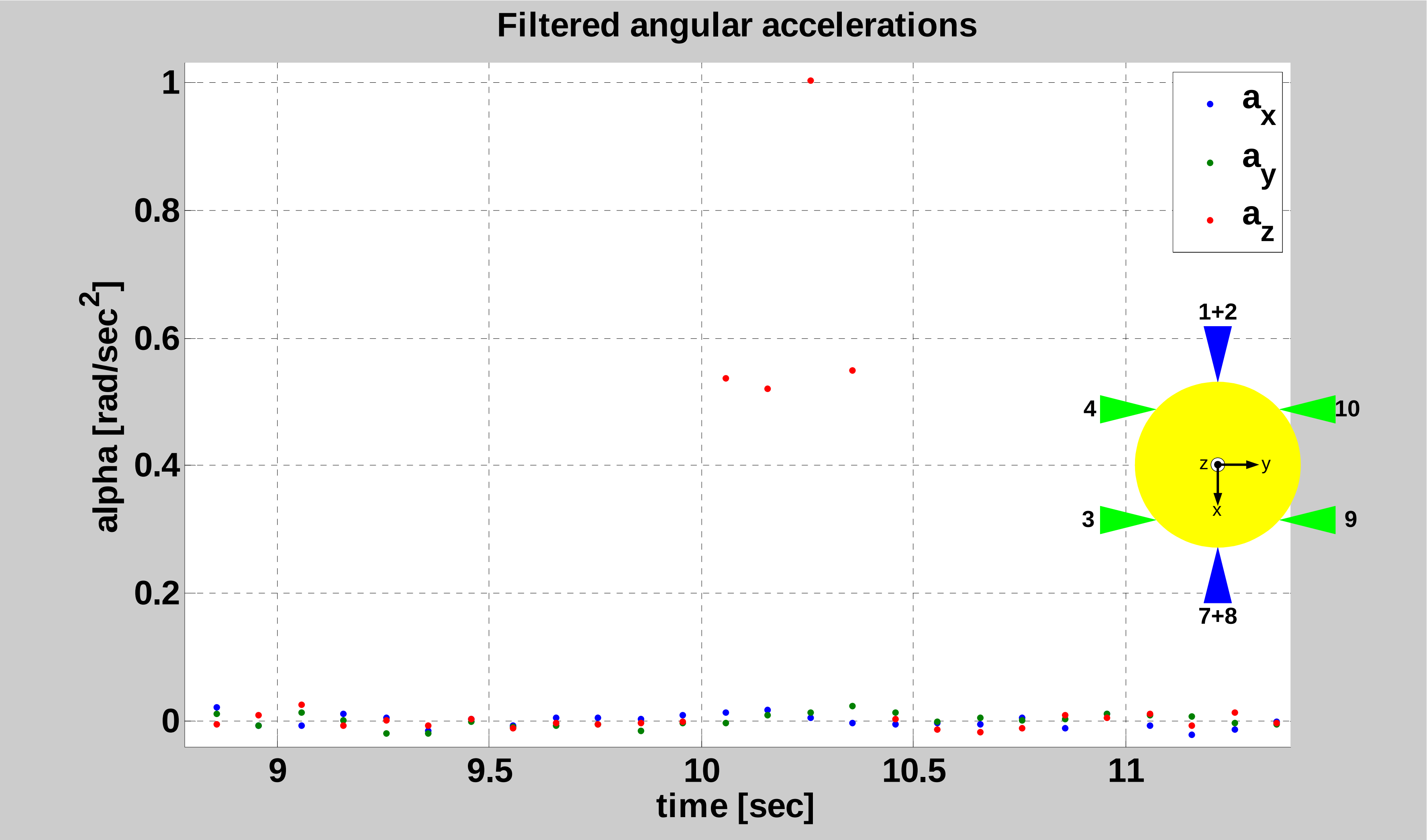
ISS013E65801

Failed on thruster FDI. No closed loop control. No thrusters commanded to fire. At ~10 seconds into the test, T3 failed on. FDI detected, isolated, and shut it down after 0.4 seconds. This test was designed as #1 since it did not rely on closed loop control, and it would be readily obvious from video whether it was successful. If FDI had failed, the stuck-on thruster would have stayed on for the remaining 6 seconds of the test.

Failed-on thruster FDI, omega



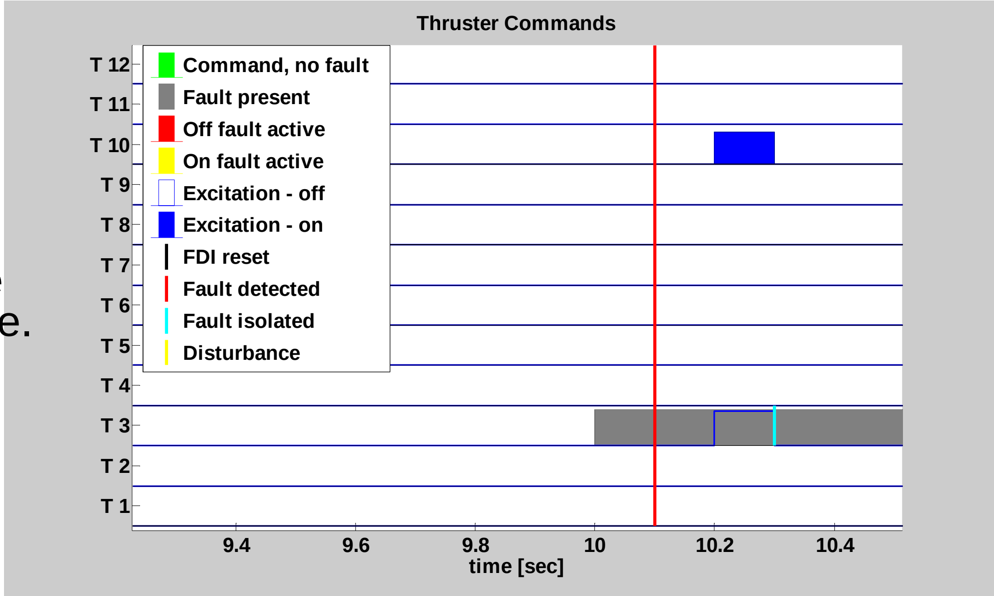
Failed-on thruster FDI, alpha

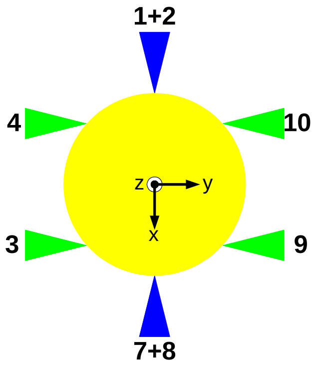


Zoomed in. The 1 rad/sec point is due to T10 being turned on as part of the excitation procedure. Very clean data (vs. KC or X-38 sim).

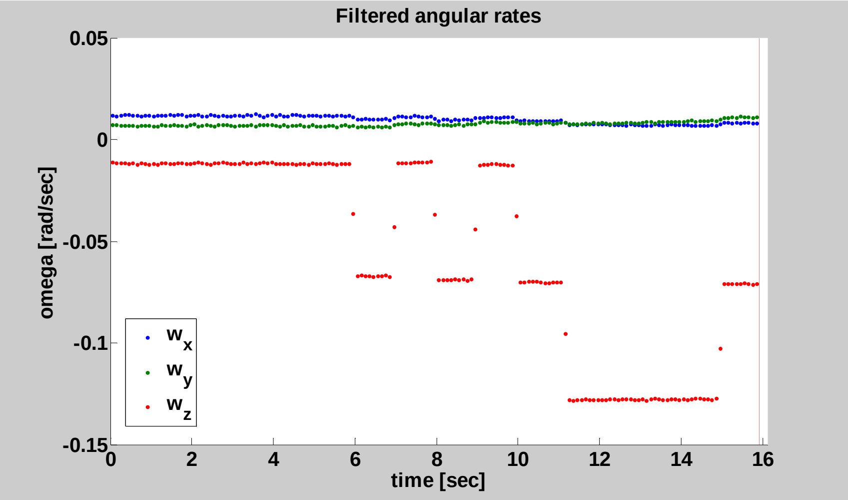
FDI execution

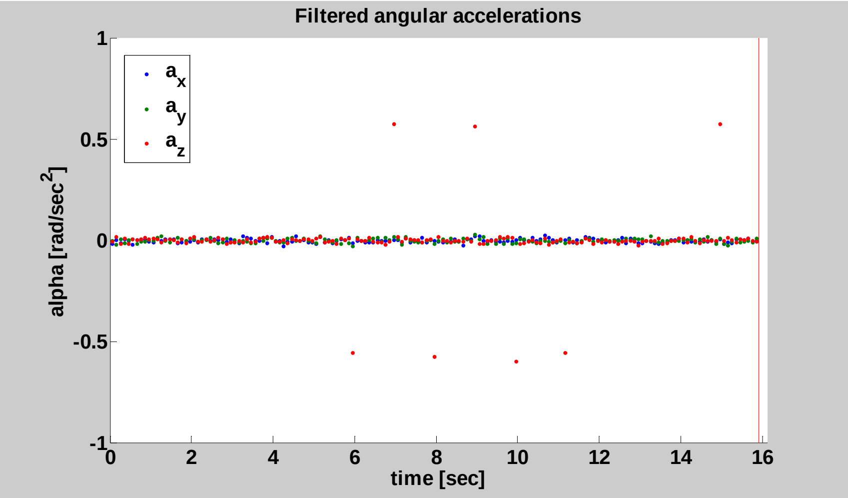
- The fault appears at t=10, indicated by the grey rectangle. T3 turns on at this time.
- The only thruster command shown here is the blue excitation-on pulse from t=10.2 to 10.3.
- A few ms into the control cycle started at t=10.1, gyro data has been filtered and the FDI detects a fault, indicated by the red line. From this single cycle of data, the FDI system has narrowed the fault down to either T3 failed on or T10 failed on.
- The t=10.1-10.2 control cycle is already underway at this point, so an excitation is planned for the t=10.2-10.3 control cycle, where T10 is commanded to fire (shown in solid blue), and T3 is commanded to not fire (in case it had been commanded to; indicated by the blue outline).
- Both T3 and T10 fire during the t=10.2-10.3 cycle, resulting in the angular acceleration value shown previously. This allows isolation of T3-failed-on a few ms into the t=10.3-10.4 control cycle, indicated by the cyan vertical line at t=10.3. T3 and (its opposite) T9 are shut down at t=10.4.

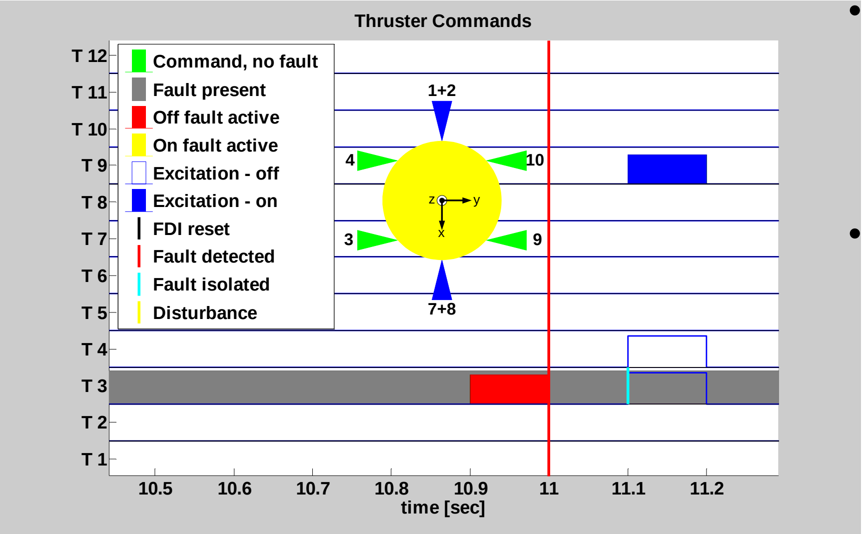




Failed-off thruster

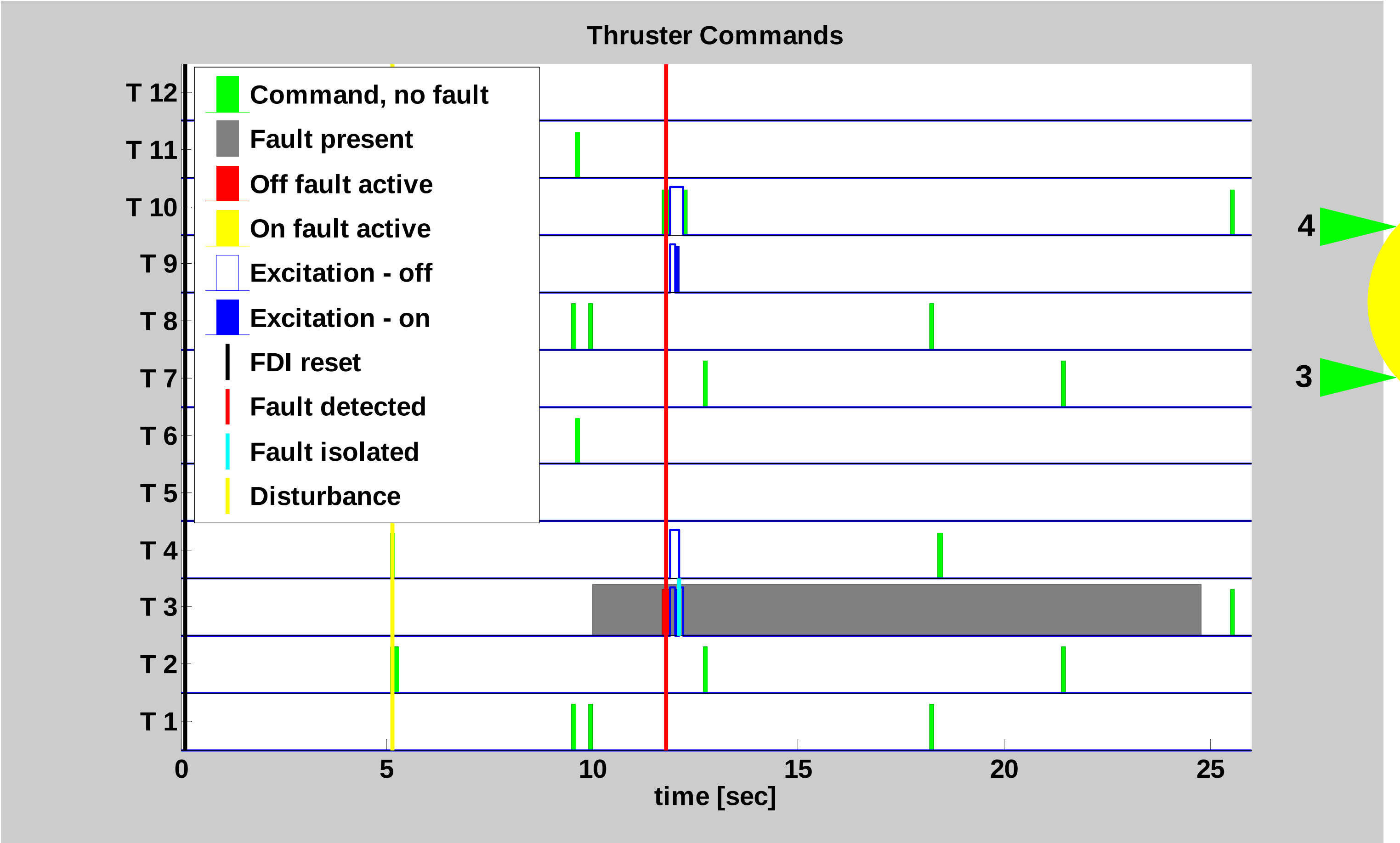


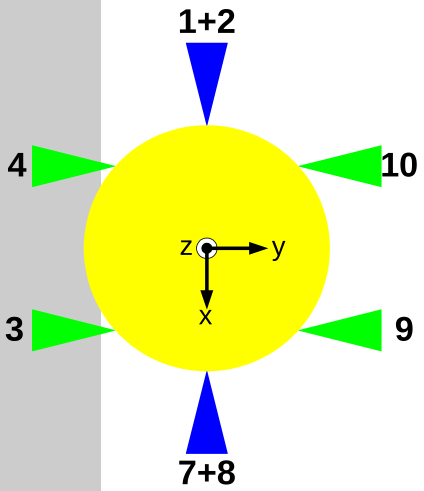




- Thrusters were disabled for the first 5 seconds; T3 and T9 fired alternating single-cycle pulses once per second; and T3 was failed off at t=10. When T3 was commanded to fire at t=10.9, it did not, as seen in the angular acceleration plot (T3 should cause a positive yaw acceleration of approximately 0.58 rad/sec2).
- The FDI system detected a fault following this cycle, shortly after t=11.0. Based on this information the remaining fault candidates were: T3 off; T4 on; and T9 on. It scheduled an excitation of T9 on, T3 off, and T4 off at the next possible time, which was between t=11.1 and 11.2. But since no thrusters were commanded to (or did) fire between t=11.0 and 11.1, the on-faults were exonerated, leaving only T3 off, which was isolated as soon as that cycle of data was filtered and processed.
- This isolation is indicated by the cyan line at t=11.1. As mentioned, the isolation actually occurred a few milliseconds later, so the excitation was already underway.

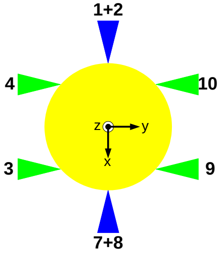
Failed-off thruster, attitude hold



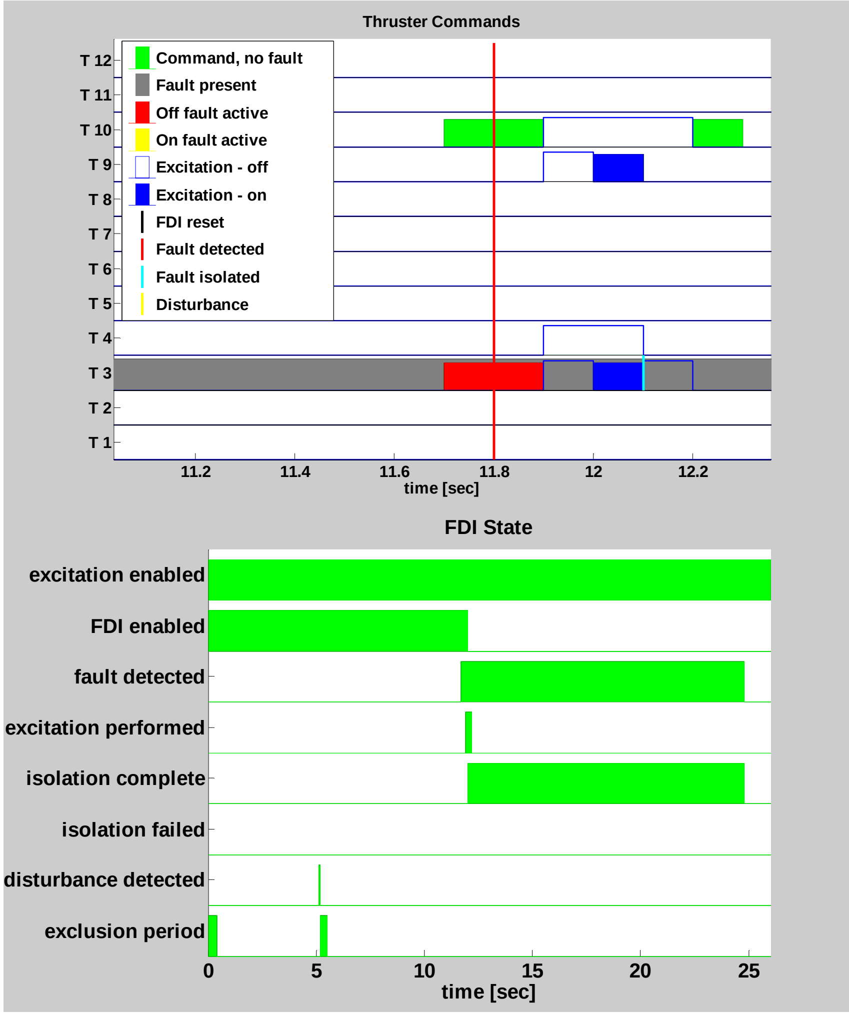


- A disturbance was (erroneously) detected shortly after t=5 when the thrusters were enabled.
- Regulation continued throughout the test, although thrusters 3 and 9 were shut off following isolation.
- The FDI executed successfully following the failed off thruster becoming active at t=11.7.

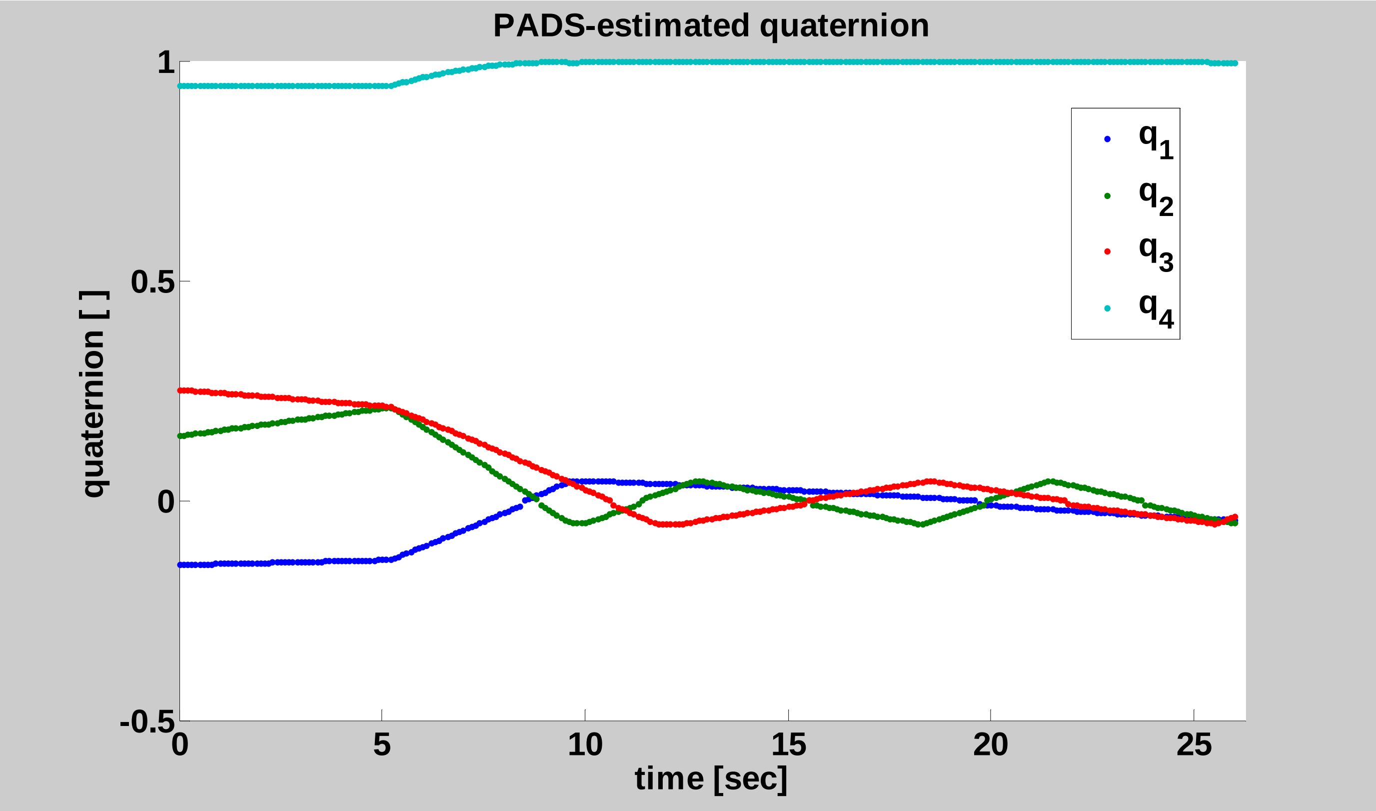
Failed off, attitude hold, FDI execution



- The off-fault becomes active at t=11.7 when T3 is first commanded to fire following the fault onset. Detection occurs immediately following this cycle, indicated by the vertical line at t=11.8.
- Since both T3 and T10 were commanded to fire during that cycle, there are 4 candidates remaining at the time of detection: T3 off, T10 off, T4 on, and T9 on. Excitation schedules all 4 of those thrusters to be off during the cycle from t=11.9 to 12.0. The Excitation algorithm prefers to turn thrusters off vs. on, as it conserves gas.
- Since the firing pattern from t=11.8 to 11.9 was the same as the preceding cycle, no new information was gained. The excitation algorithm schedules T3 and T9 on (these are directly opposing, so if neither has failed, no disturbance will result, making for a less disturbing excitation), and T4 and T10 off from t=12.0 to 12.1. It has to do this before getting results of the first excitation pattern, but it selects the second pattern considering the knowledge it will gain from analyzing that first pattern.
- With off-excitation ensuring that no thrusters are commanded to fire from t=11.9-12.0, and when no firing is detected, the on-fault candidates are exonerated, leaving only T3 off and T10 off as candidates.
- The excitation pattern from t=12.0-12.1 commands T3 and T9 to fire. When this data is analyzed shortly after t=12.1, showing a disturbance, fault T3-off is correctly isolated.



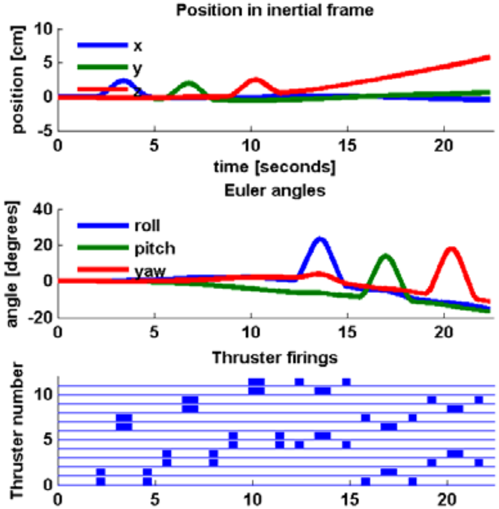
Attitude hold performance

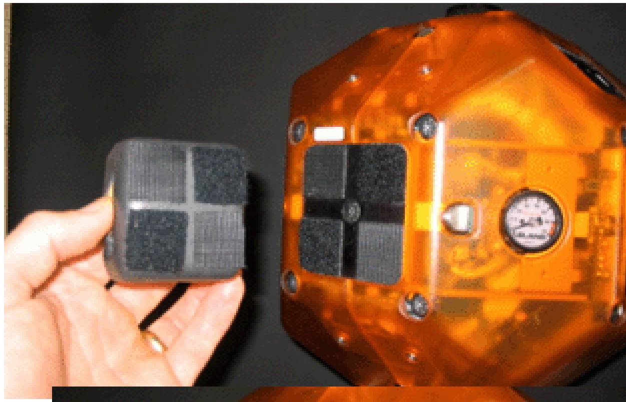


- The quaternion plot shows the initial correction towards zero following enabling the thrusters at t=5, and that this attitude hold is maintained even while the thruster fault occurs and is detected, isolated, and shut off, along with its opposing thruster.

ISS Mass ID testing

- Ran on 8/12/06 in SPHERES Test Session 3. Thruster faults observed. Some due to IR interference. Data analyzed and used to refine next iteration.
- Next tests to be run on 10/27/06.
- Experiments:
  - Open-loop firing sequences
  - Single-axis (2-thruster) firings
  - Single-thruster firings
  - Fuel-slosh excitation
  - 2-axis spins
  - 1-axis spins
  - Proof mass attached
  - Docked to second SPHERE ID properties of passive spacecraft





Summary, Future Work

- Algorithms and flight-test validation for motion-based thruster FDIR and mass-property ID
  - Maximum-likelihood-based thruster FDI
  - Developing underactuated reconfiguration, with focus on docking
  - Computationally efficient RLS-based mass-property ID
- Useful both together and standalone
- Utilize existing navigational sensors – gyros, accelerometers, etc.
- Software-only solution. Implementable on- or off-board.
- Can augment sensor-based FDI (e.g., on Space Shuttle Orbiter)
- Runs in background – no special motions required
- Applicable to broad class of spacecraft, especially small, unmanned, maneuvering spacecraft that are subjected to significant mass-property uncertainty, due either to fuel consumption, internal reconfiguration, or the carrying of variable payloads
- Generic algorithms successfully applied to multiple vehicles in simulation and hardware

- 3rd SPHERES to be delivered by Shuttle in December 2006.

- Papers, presentations, videos available at http://intellization.com/files/

- SPHERES P.I.: Prof. Dave Miller: millerd@mit.edu

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