Motion-Based Thruster Fault Detection and Isolation

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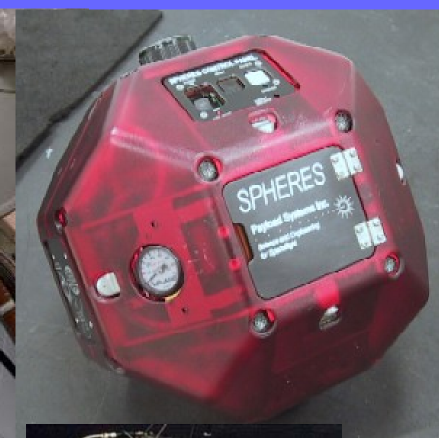
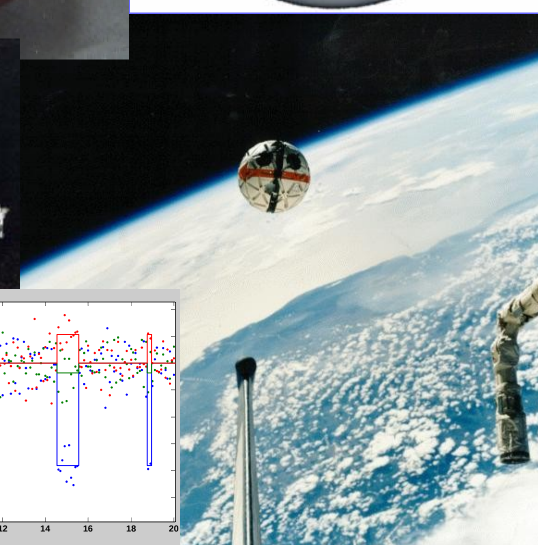
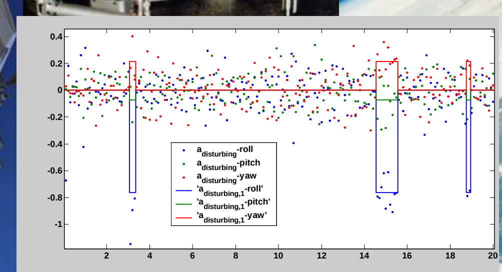
Research objective: For thruster-controlled spacecraft, increase **on-line thruster fault tolerance** using existing navigation sensors (gyros, optionally accels)—a software-only solution. Develop and validate through application on realistic simulations and hardware. Flight test on MIT SPHERES aboard ISS in 2006.

Outline:

- Thruster FDI
- Maximum-likelihood FDI
- X-38 MATLAB Demo
- SPHERES
- Air table tests / ISS plan
- Conclusions

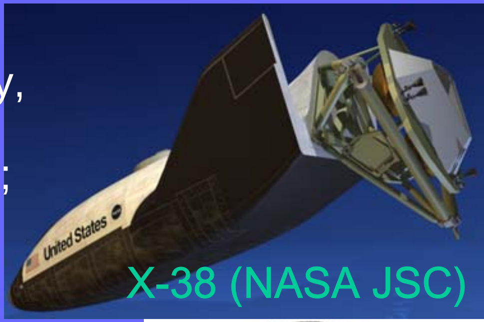




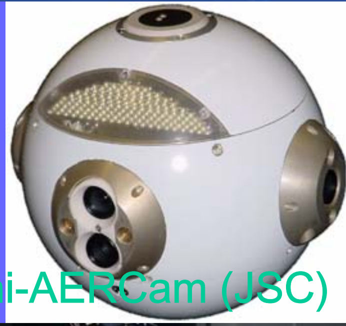


Thruster fault detection and isolation (FDI)

- 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



X-38 (NASA JSC)


Mini-AERCam (JSC)


S4 (NASA Ames)

SPHERES (MIT SSL)

X-38 application overview video

Thruster FDI approaches taken

- 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

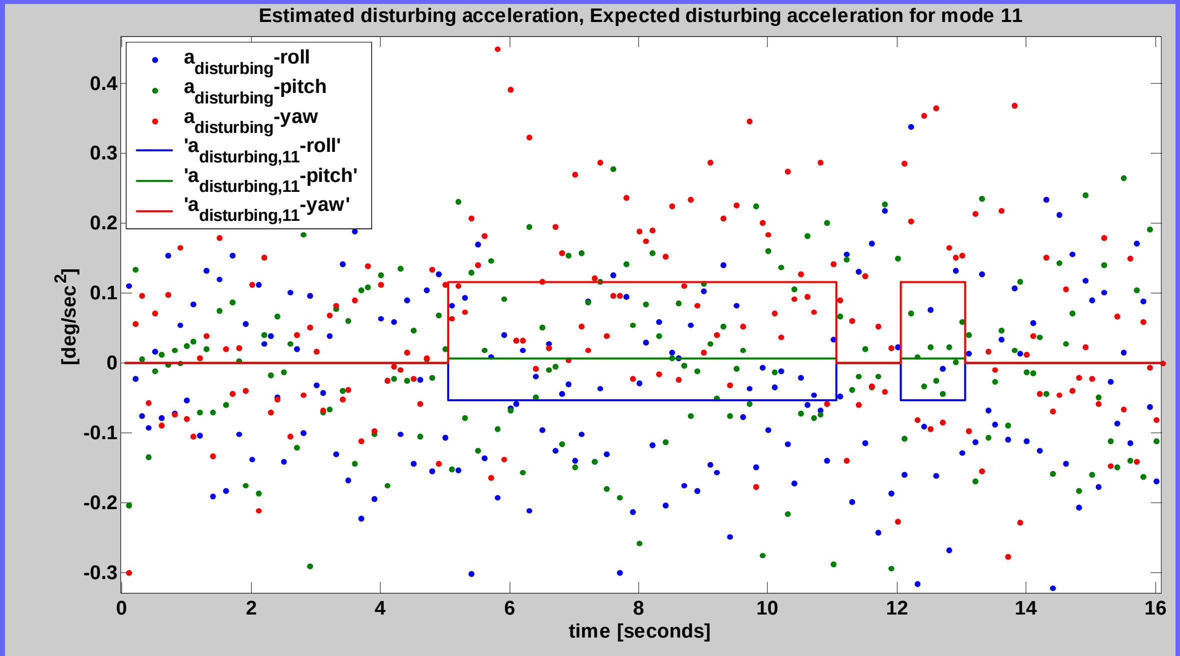
- Difficulties presented by low SNR and biases – exceptionally challenging for X-38, as compared to Mini-AERCam, S4, Stanford Free-Flying Robot, SPHERES

Maximum Likelihood FDI

- Algorithm's **core** based on a 1976 paper by Deyst and Deckert on leak detection for the Space Shuttle Orbiter
- Calculates difference between expected and actual angular acceleration
- Compares this "disturbing acceleration" to that corresponding to the possible fault modes
- Due to low SNR and fault modes with similar disturbing accelerations, **filtering and windowing** data required
- Detection based upon generalized likelihood ratio (GLR) test for each fault mode
- Identification based on the likelihood calculation for each fault mode
- Excitation of thrusters required in some cases
- **Logic** to exonerate some faults, isolate correct fault mode

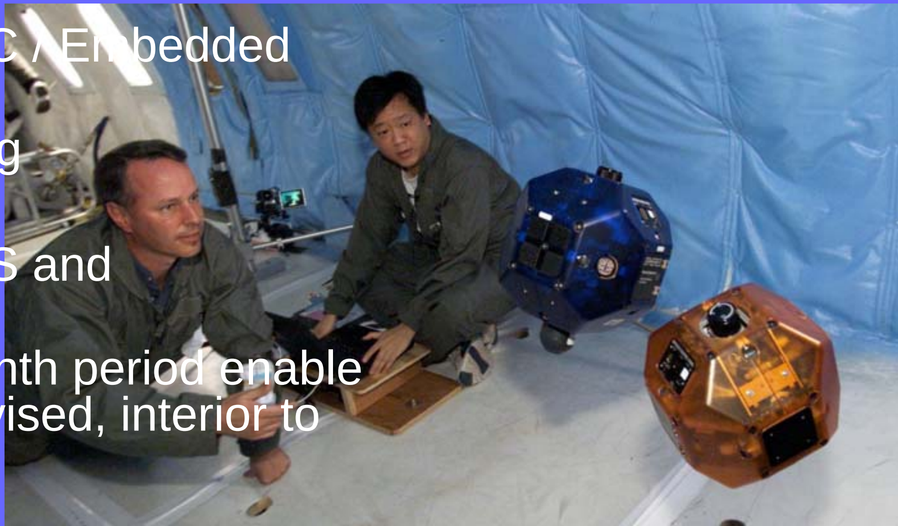
FDI Performance

- Generally detects fault within 1 second (active time) for X-38, faster for Mini-AERCam
- ID follows within 1-5 seconds for X-38 (slower when blowdown multiplier low)
- FDI developed on X-38, then easily “ported” to Mini-AERCam, S4, SPHERES. Significantly easier problem due to better SNR and fewer, less complex fault modes.
- Simplified (non-windowing) algorithm implemented for SPHERES.
- Extended automatic testing run for X-38 – 99.9994% accurate FDI (without miss or incorrect ID)
- MATLAB demo

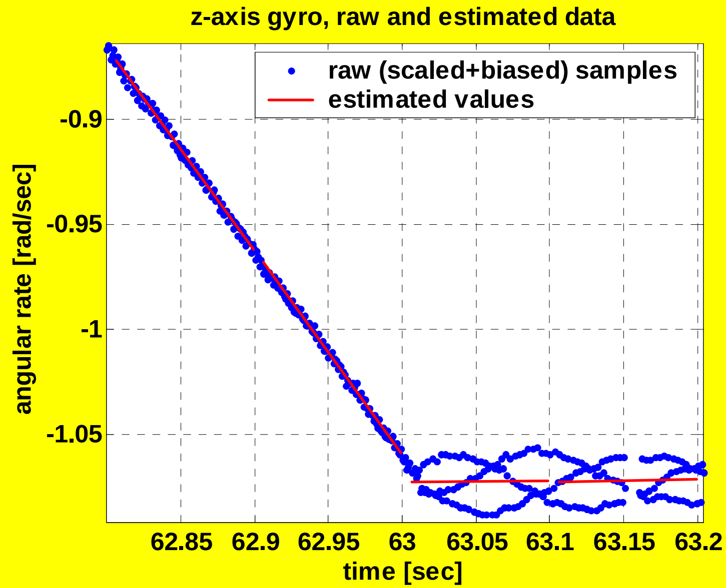


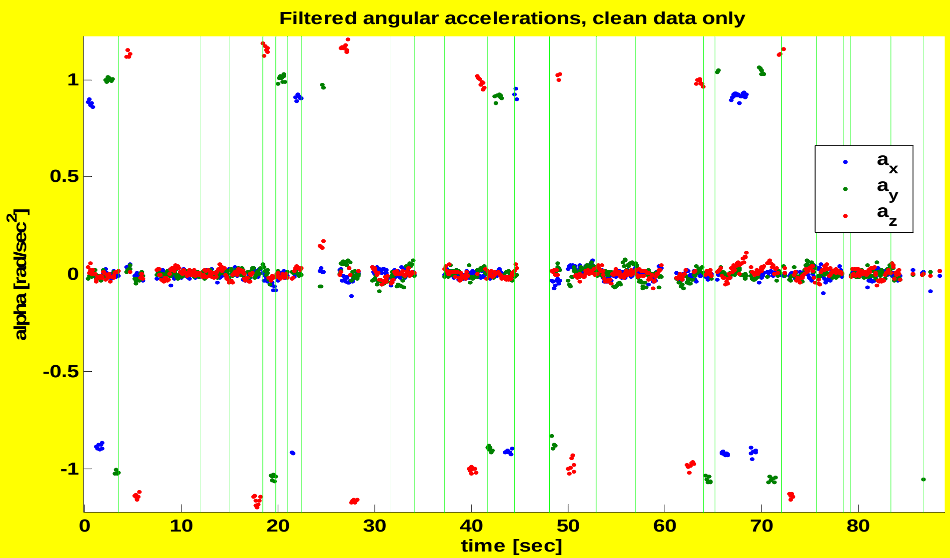
SPHERES properties

- Synchronized Position Hold Engage Reorient Experimental Satellites
- MIT Space Systems Lab / Payload Systems Inc.
- 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
- Approx 10 2-hour experiments over 8-month period enable ***experimental iteration***. Astronaut supervised, interior to ISS.



SPHERES angular acceleration estimation from on-board filtering





- SPHERES, NASA KC-135 data
- Controller runs at 10 Hz, gyros sampled at 1 kHz
- Omega, alpha filtered on-board for every 100 ms control segment
- Acceleration estimation critical to FDI
- Inertial sensors generally susceptible to vibrations, as shown
- With careful filtering, resulting angular acceleration estimates make SPHERES implementation far simpler than X-38

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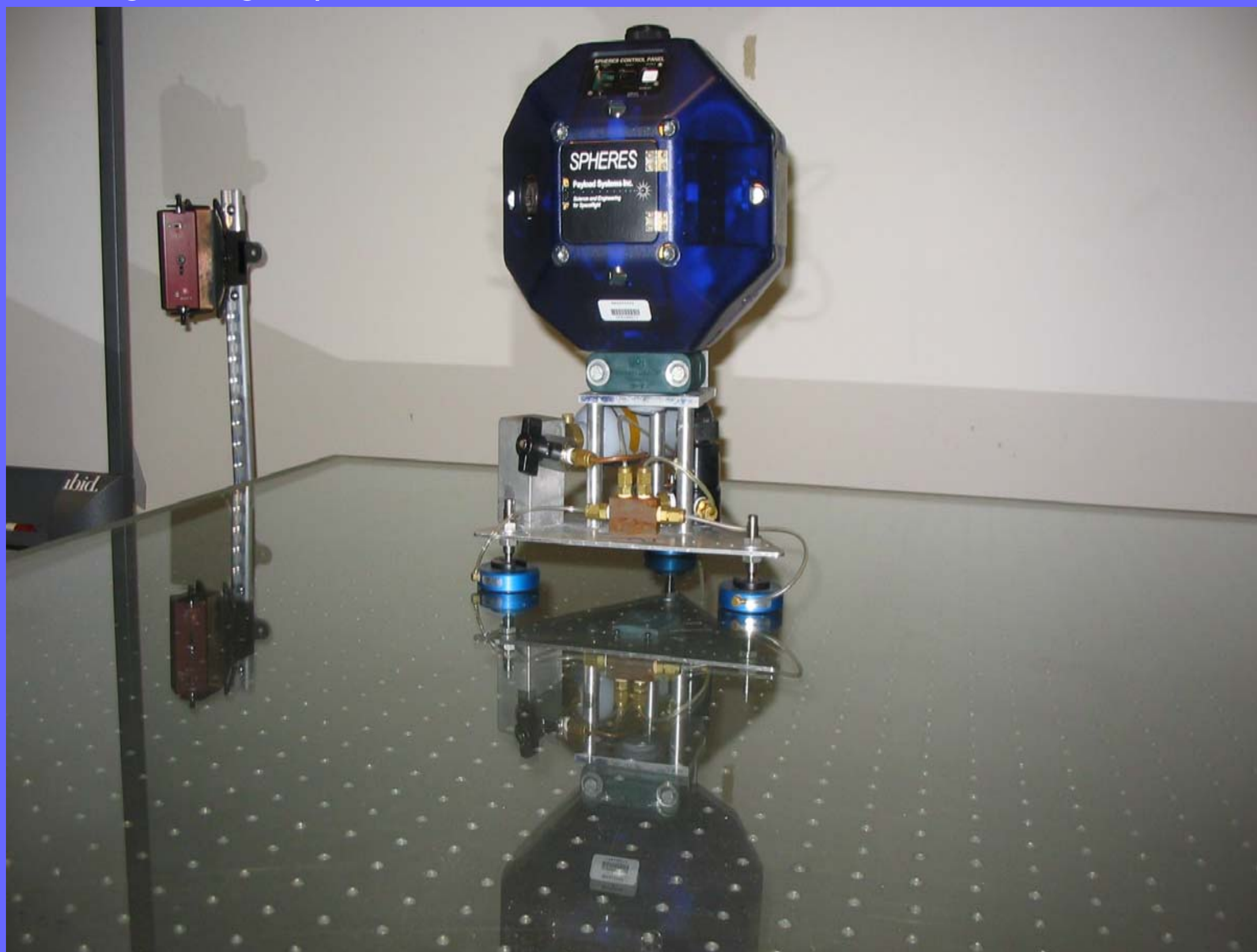
Simplified FDI algorithm for SPHERES

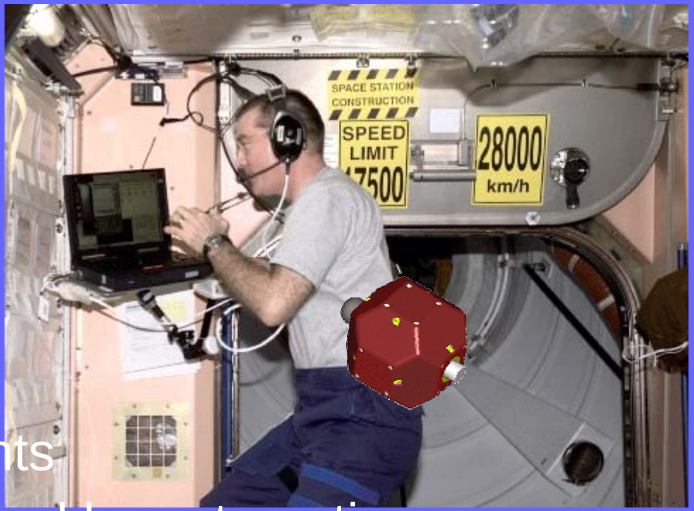
- For SPHERES (and likely many S/C other than the X-38), the windowing aspect of the algorithm is not needed.
- Simplified version implemented in flight code:
  - 24 thruster accelerations (also fault signatures) pre-calculated – 6x24 matrix, automatically generated C code based on vehicle properties
  - 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 FDIR on air bearing table

- Test conducted at NASA Ames Research Center
- Regulating to fixed position/attitude
- Fault initiated in software, detected, isolated, and simple reconfiguration implemented
- Continues regulating to position, without full attitude control



SPHERES ISS experimental plan



- STS-121 launch, STS-116 re-supply
- Iterative experiment sessions
- 1st session is Mass-property ID
- 2nd session is initial thruster FDI
  - Closed loop position and attitude control
  - Controlled to follow sequence of way-points
  - Initiate thruster-off fault in software, followed by automatic FDI and simple R
  - Repeat with different thrusters, on and off faults
- Simple reconfiguration does not control attitude on axis with lost thruster – underactuated control
- Subsequent sessions:
  - Multiple faults
  - More advanced control reconfiguration
  - Docking following thruster fault

Conclusions

- Maximum-likelihood-based FDI presented for thruster fault detection
- Applied high performance versions to X-38, Mini-AERCam in simulation, simplified version to MIT SPHERES in hardware
- Allows thruster FDI using (existing) navigational sensors – gyros, accelerometers, etc.
- Generic algorithm applied to several vehicles
- Enables software-only FDI
- Presented experimental plan for ISS SPHERES tests

- Paper, presentation, video are available at http://intellization.com/files/

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