Motion-based system ID and FDI for thruster controlled spacecraft

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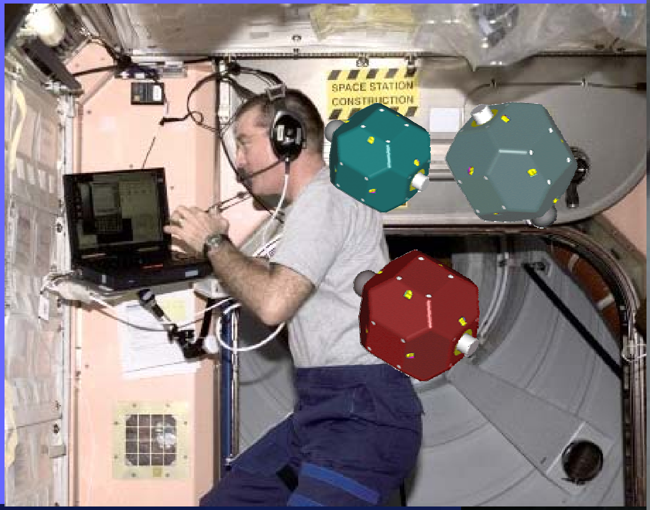
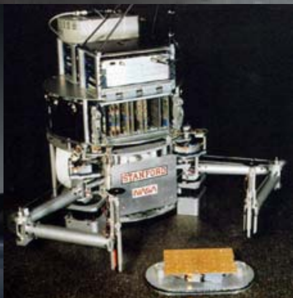
Research objective: Extend, implement, and test *motion-based* ***thruster FDI*** and ***mass-property ID*** technologies for thruster controlled spacecraft. Flight test on the MIT SPHERES experimental spacecraft operating on the ISS in 2004.

Outline:

- Introduction
- Thruster FDI
- Mass ID
- SPHERES
- KC-135A results
- Conclusions





Introduction

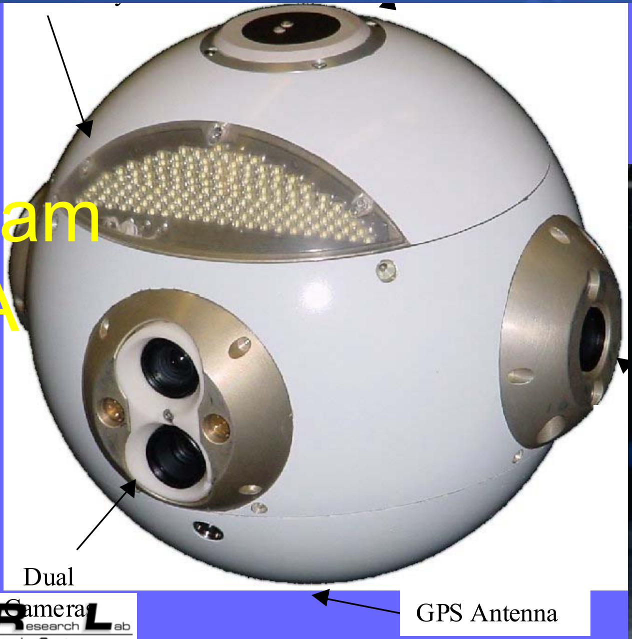
- Technologies for thruster-controlled spacecraft:
  - **Thruster Fault Detection and Isolation** (FDI)
  - **Mass-property ID** (CM location and inertia matrix)
  - FDI and ID are motion-based (**gyros** are sufficient)
  - Generic technologies developed through application to specific problem statements provided by JSC for X-38 and Mini-AERCam
  - Software-only solution (uses existing sensors)
  - Applicable to a broad class of spacecraft
- **Implementing for SPHERES** – to fly on ISS in 2004

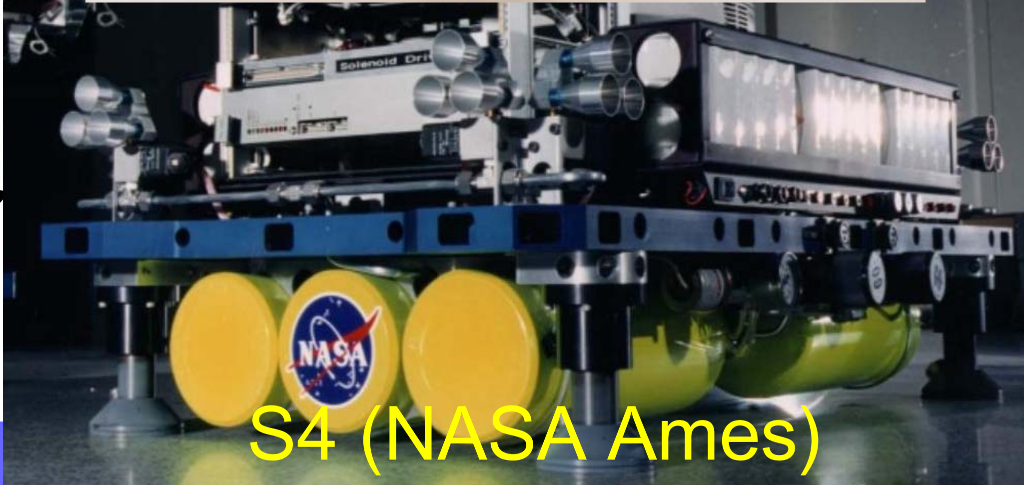
Spacecraft tested in Simulation

X-38 v.201 (NASA JSC)

SPHERES (MIT/PSI)

Mini AERCam (NASA JSC)





S4 (NASA Ames)

Motion-based thruster FDI

- Goal: Increase thruster fault tolerance using existing navigation sensors only (a software-only solution).
- Spacecraft thrusters – on/off, failure modes
- Sensor-based FDI uses temperature, pressure, electrical sensors – increased mass, cost, complexity
- Motion-based FDI most applicable for small, maneuvering spacecraft (vs. human-rated)
- FDI → R by switching to backup or reconfiguring control
- Compared with existing body of FDI, presence of on/off actuators a problem
- Related research: Deyst and Deckert (MIT/Draper) 1976, Lee and Brown (JPL) 1998, Wilson and Rock (Stanford ARL) 1995

Thruster FDI development

- Failure modes:
  - Single- and multiple-jet
  - Abrupt, hard
  - Failed-on or failed-off
- Development approach:
  - Working from a very detailed (and realistically specified) problem statement for the X-38 from JSC ➔ very challenging due to SNR, all other vehicles (Mini-AERCam, S4, SPHERES) easy after X-38 was solved.
  - Test in simulation / lab hardware
  - Generic as possible – applicable to other spacecraft

Thruster FDI approaches taken

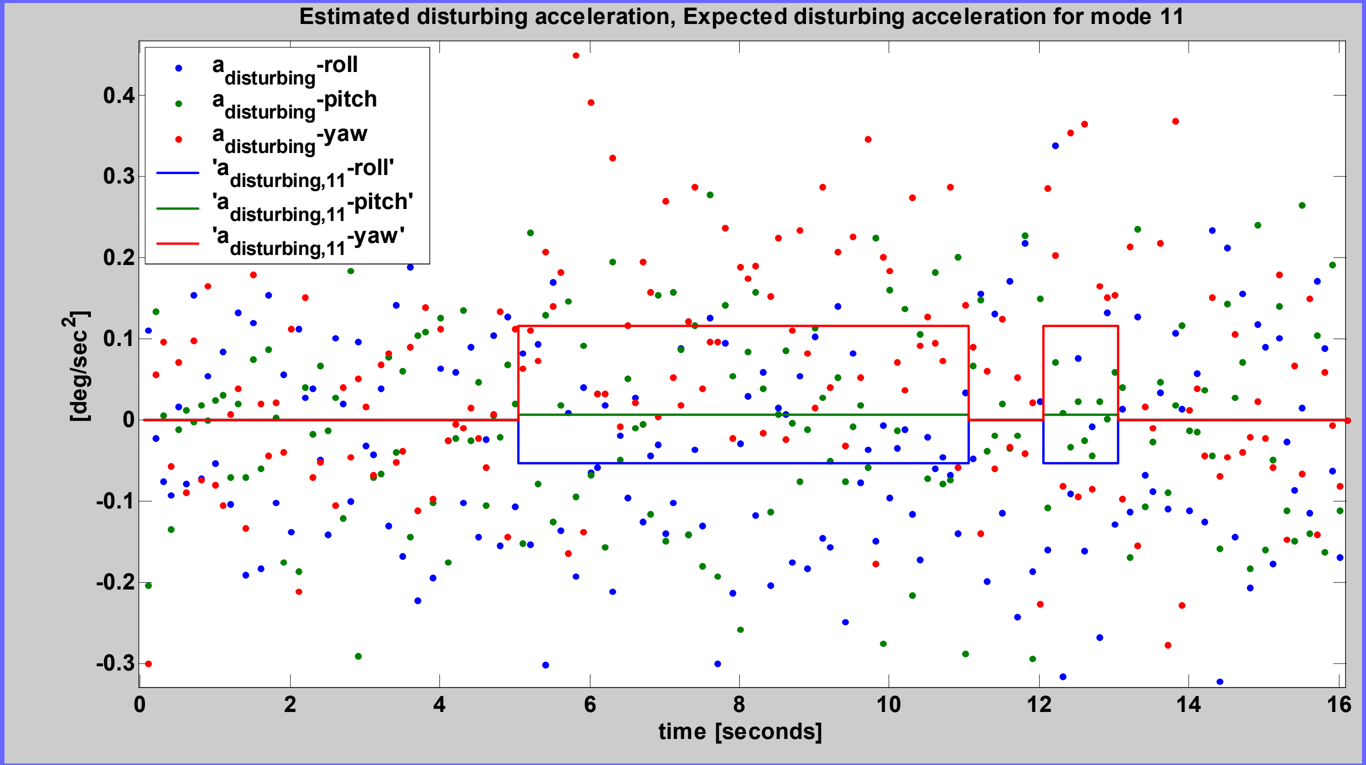
- Recursive Least Squares (RLS) – Simultaneously ID all thruster strengths, declare failure when out of spec.
- Targeted RLS – One RLS process running for each thruster.
- Bank of Kalman Filters – One (steady state) KF running for each failure mode, examine residuals.
- Maximum Likelihood – Determine the failure mode whose resulting accelerations most closely match the measured angular accelerations

- Challenge is optimizing response time while maintaining accuracy.
- Difficulties presented by low SNR and biases – exceptionally challenging for X-38, as compared to Mini-AERCam, S4, Stanford Free-Flying Robot

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 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
- Identification 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

Performance



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 – 99.98% accurate FDI
- FDI developed on X-38, then easily “ported” to Mini-AERCam, S4, and SPHERES.

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)
  - Mass properties can significantly impact advanced control, estimation, and FDI calculations
- 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

Least-squares identification (LS ID)

- Cast governing equations into form $\boldsymbol{Ax} = \boldsymbol{b} + \varepsilon$
- Noise appears in ε
- Parameters to ID appear (linearly) in $\boldsymbol{x}$
- Closed form solution minimizes sum squared error: $\hat{x} = \left(A^T W A\right)^{-1} A^T W b$
- Batch or equivalent recursive solutions (RLS)

- *Challenge is in manipulating governing equations into correct form,* $\boldsymbol{Ax} = \boldsymbol{b} + \varepsilon$

Problem characteristics / Approach

- Full dynamics involve:
  - Thruster strength and alignment
  - Inertia matrix
  - CM location, Mass
- Variability:
  - Pulse-to-pulse thruster variation
  - Sensor noise
  - Disturbance forces and torques
- Parameters appear in governing equations of motion (EOM) coupled, nonlinear
- Approach: divide into separate approximate linear solutions
- Separate RLS IDs for inertia, CM, thruster strength

Mass-center ID algorithm

Equations of motion:

$$\dot{\omega} = I^{-1}((L \times D)B(F_{nom} + F_{bias} + F_{random,k})T_k + \tau_{disturb} - \omega \times (I\omega))$$

Manipulated EOM:

$$C \equiv C_{nom} + \Delta; L = L_{nom} - \Delta\begin{bmatrix} 1 & 1 & \dots & 1 \end{bmatrix}$$

$$I^{-1}\begin{bmatrix} 0 & -c_3 & c_2 \\ c_3 & 0 & -c_1 \\ -c_2 & c_1 & 0 \end{bmatrix}_k \begin{bmatrix} \Delta_1 \\ \Delta_2 \\ \Delta_3 \end{bmatrix} = \dot{\omega} + I^{-1}(\omega \times (I\omega)) - I^{-1}(L_{nom} \times D)F_{nom}T_k; c_k \equiv DF_{nom}T_k$$

LS (or RLS) formulation: $A_k x = b_k$

$$A_k = I^{-1}\begin{bmatrix} 0 & -c_3 & c_2 \\ c_3 & 0 & -c_1 \\ -c_2 & c_1 & 0 \end{bmatrix}_k ; x = \begin{bmatrix} \Delta_1 \\ \Delta_2 \\ \Delta_3 \end{bmatrix}; b_k = \dot{\omega} + I^{-1}(\omega \times (I\omega)) - I^{-1}(L_{nom} \times D)F_{nom}T_k$$

RLS, batch LS solution

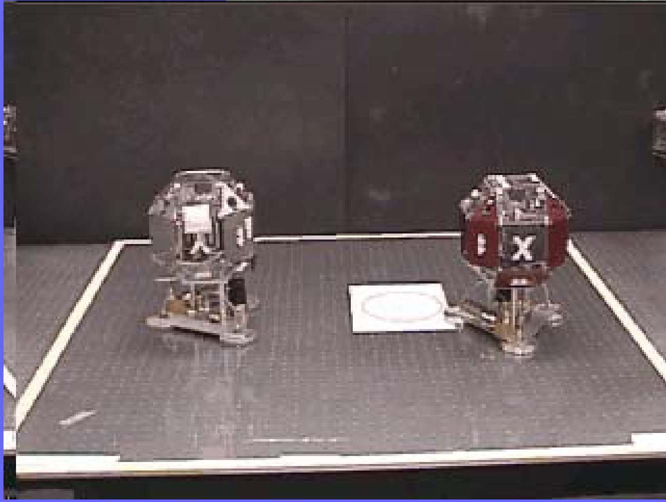
- RLS implementation: use A_k, b_k at each update, either exponentially weighted or unweighted. Use standard RLS equations.
- RLS modified slightly to avoid need for any matrix inverses
- Batch LS: concatenate A_k matrices and b_k vectors, using any desired weighting

$$A = \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_k \end{bmatrix}; b = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_k \end{bmatrix}$$

- Solve using standard batch LS solution

$$\hat{x} = \left(A^T W A\right)^{-1} A^T W b \qquad \hat{x} = \left(A^T A\right)^{-1} A^T b$$

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).
- 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. [MIT presentation material]

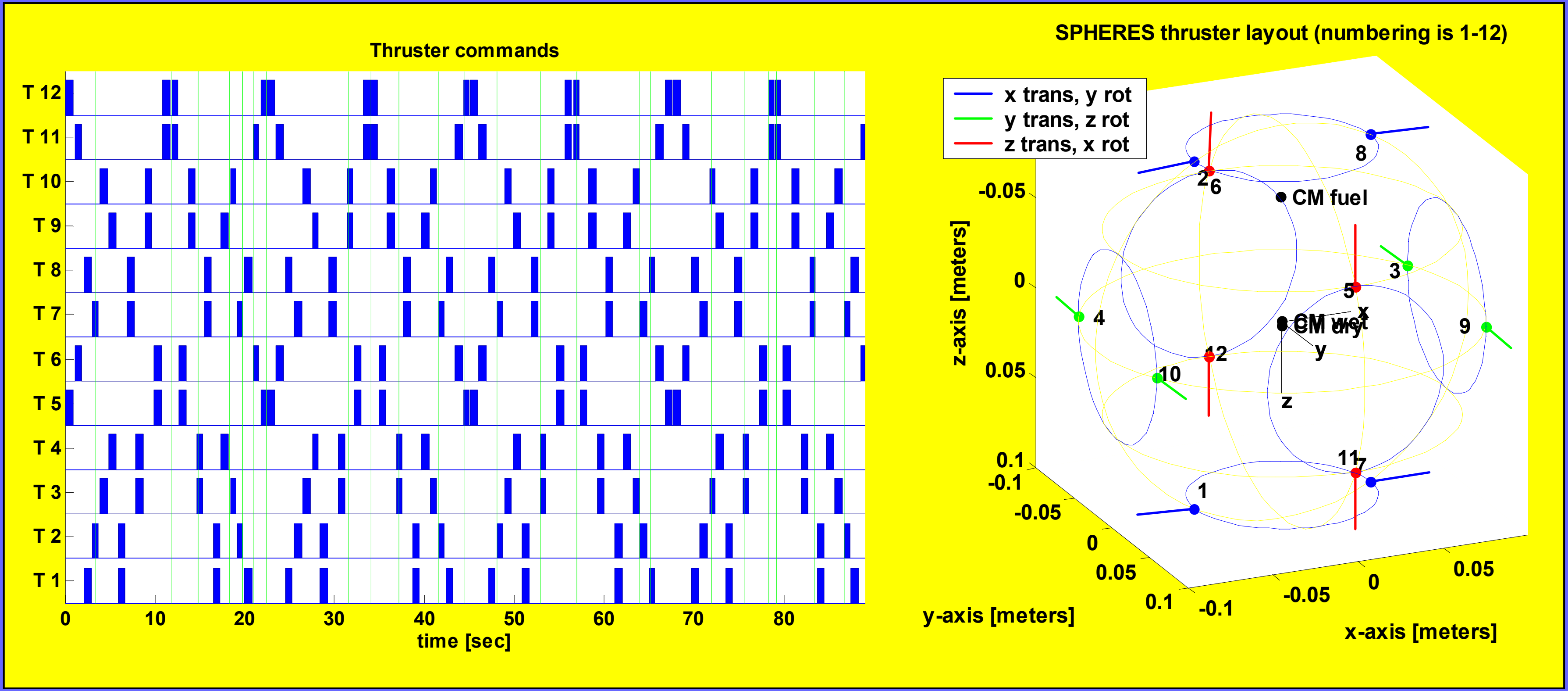
SPHERES properties

- 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
- Approx 10 2-hour experiments over 8-month period enable experimental iteration. Astronaut supervised, interior to ISS.

Nov 2003 KC-135A flight tests of MassID

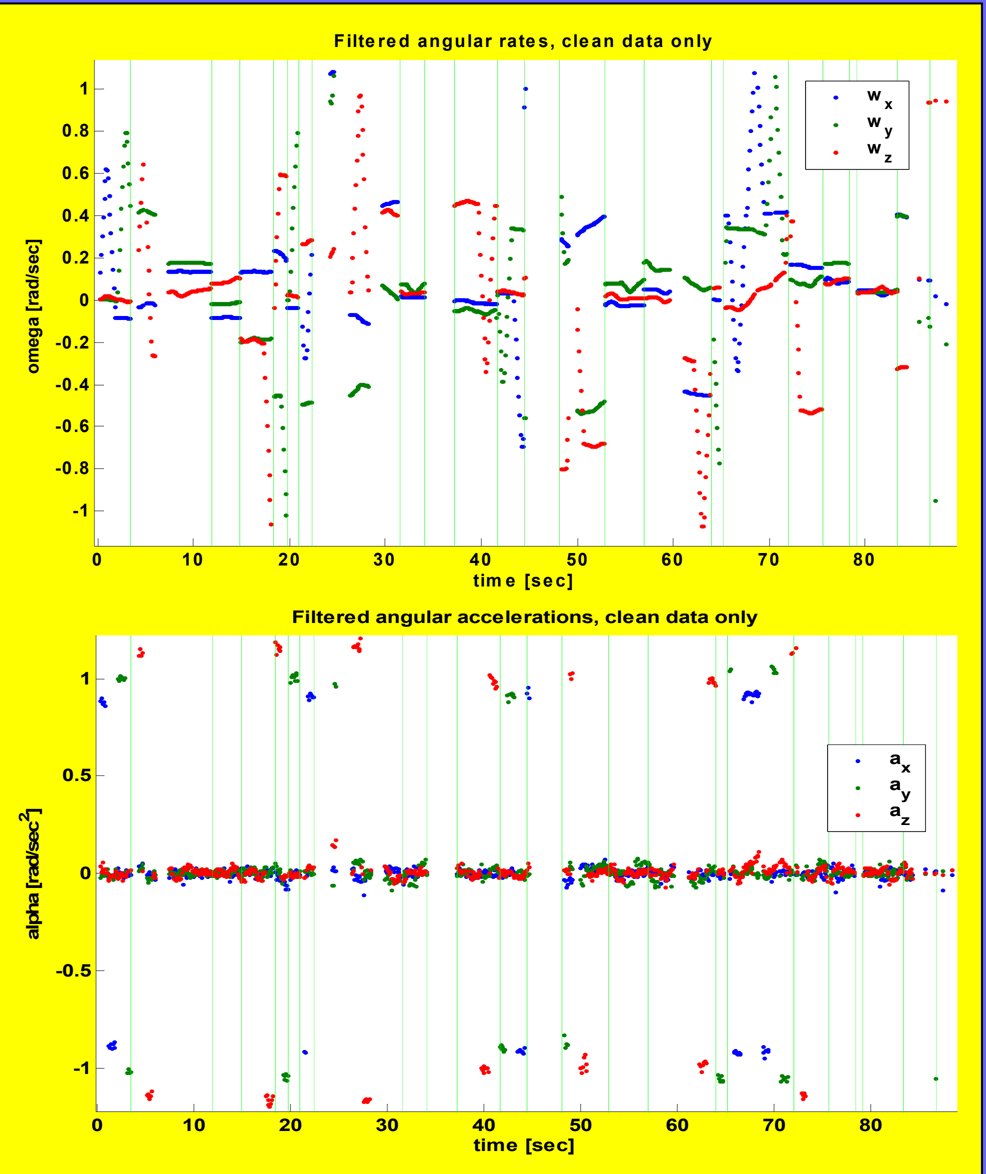
- 25 parabolas ~ 250 seconds of zero-g
- Validated implementation of mass ID algorithms, telemetry, etc.
- Open loop sequence – nominally one axis at a time (simplest)
- Tested critical issue – on-board filtering to estimate angular accelerations
- Gyroscopic term was observed and added directly to the inertia ID
- Following data from 9-parabola run on 8 Nov 03. Pause periods indicated by green lines.

Open loop thruster sequence



- SPHERES – symmetric thruster layout, 12 thrusters controlling 6 axes.
- Although arbitrary thruster inputs/motions possible (except for gyro saturation, excessive rapid fire to excite gyro ringing), simplified sequence nominally one axis at a time.
- Rotational, translational. Results in periods of ~flat ID updating on non-excited axes

Angular rates and accelerations from on-board filtering

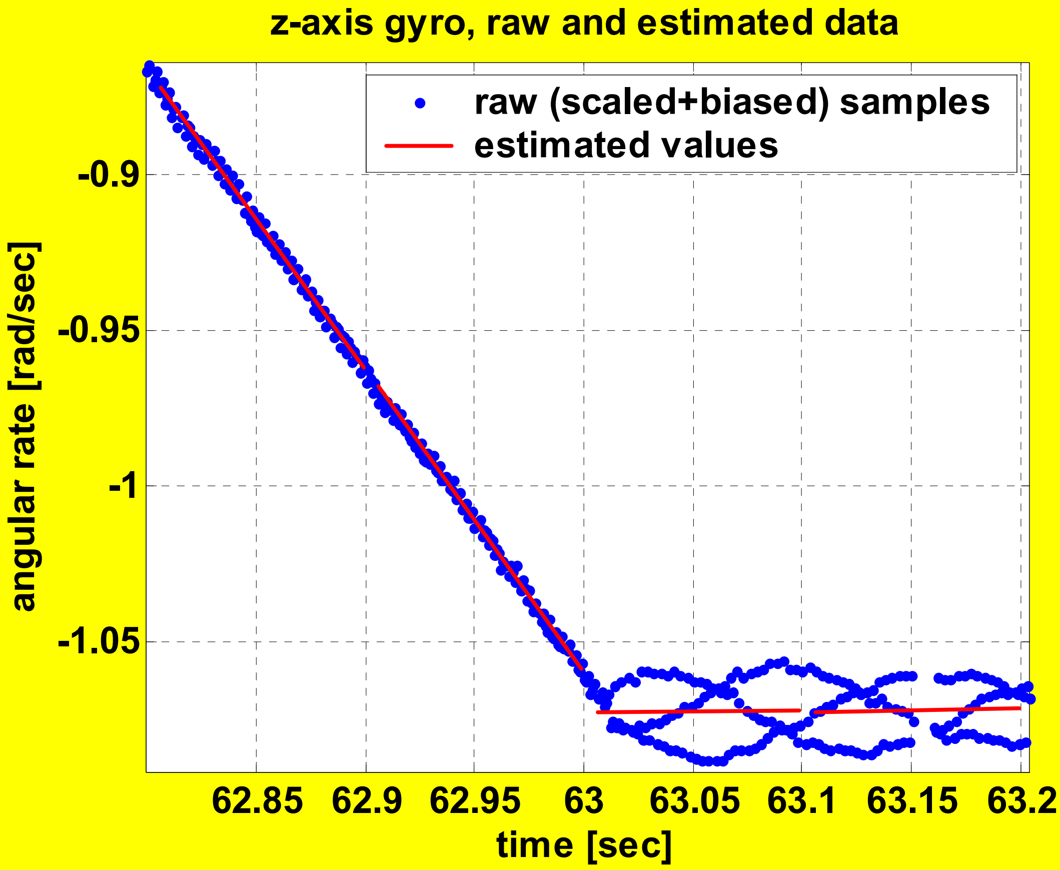


Filtered angular rates, clean data only

Filtered angular accelerations, clean data only

- 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

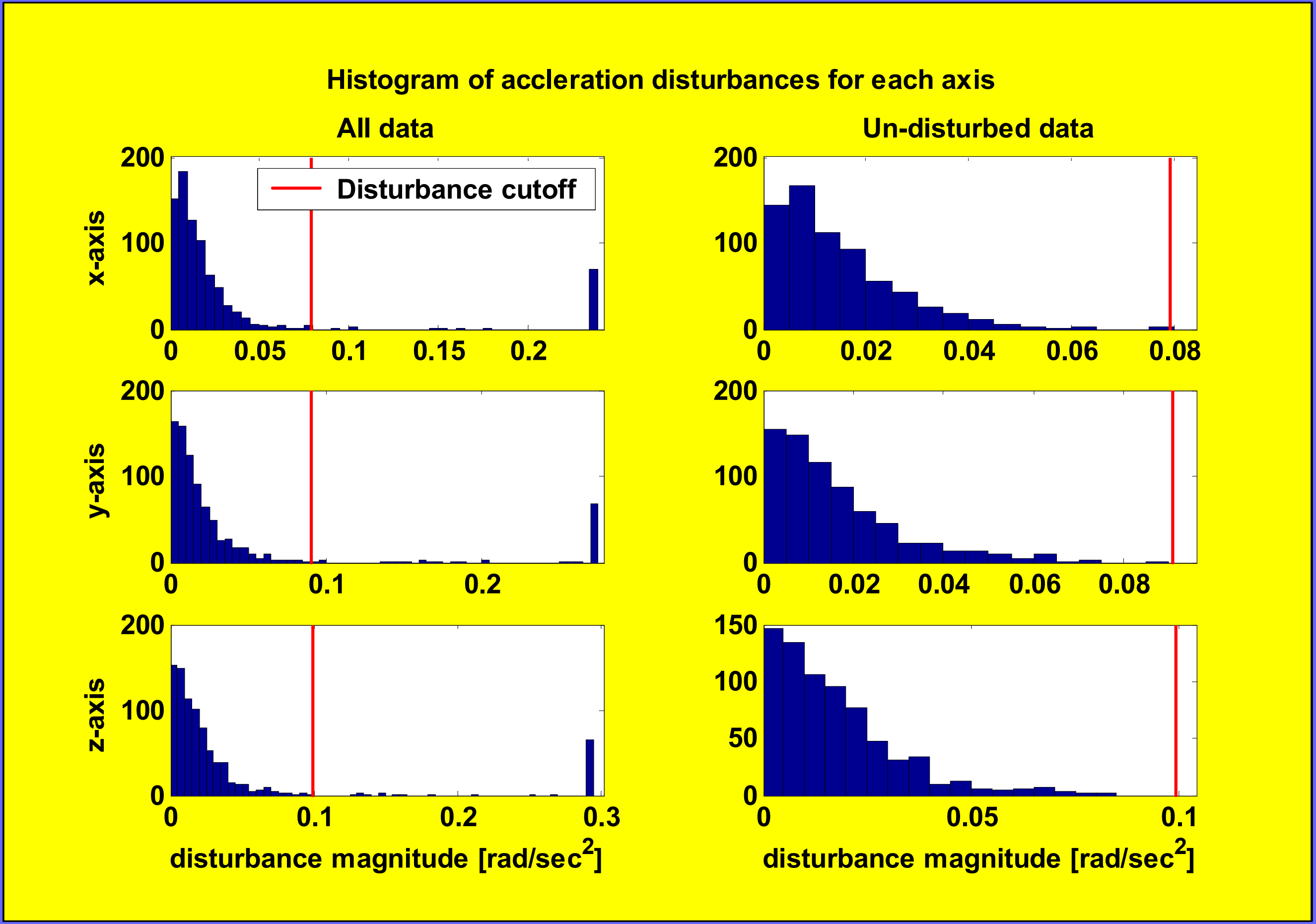
Acceleration estimation performance



Estimated segment accelerations:
-0.9665 -0.9773 0.0133 0.0167

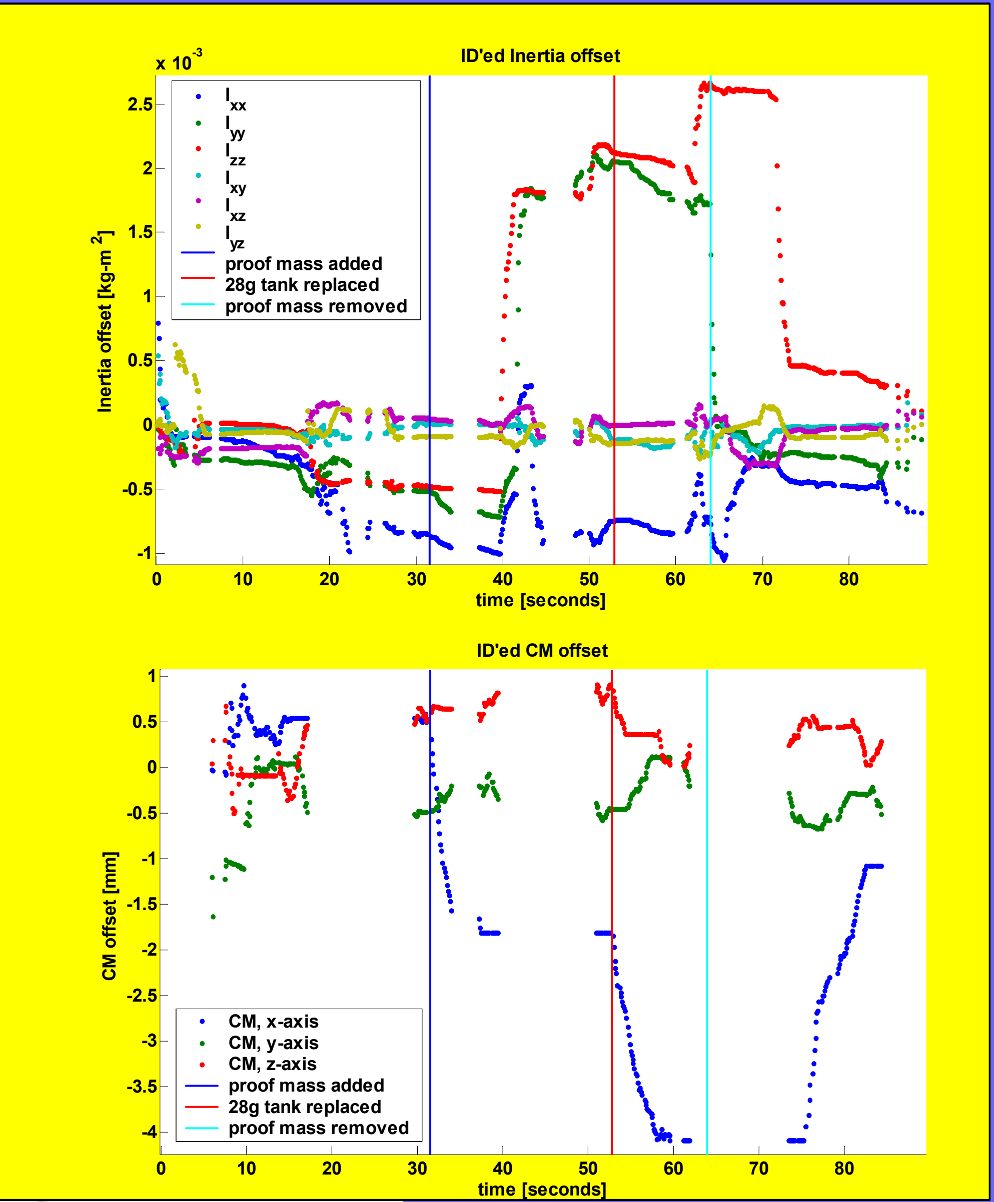
- Accurate acceleration estimation is critical to FDI and ID
- In general can be derived from other sensors (star tracker, video sensor, etc.). Gyros used here.
- Inertial sensors generally susceptible to vibrations – ringing here for the BEI Gyrochip II tuning fork rate sensor
- Accurate estimation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

Data cleaned to remove samples during handling



- “Disturbances” shown here indicate deviations from expected ➔ include estimation error, thruster variability, inaccurate nominal values, etc.
- Plots indicate clean estimates, that true handling periods are clearly detected and removed

Inertia and CM ID results



- 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

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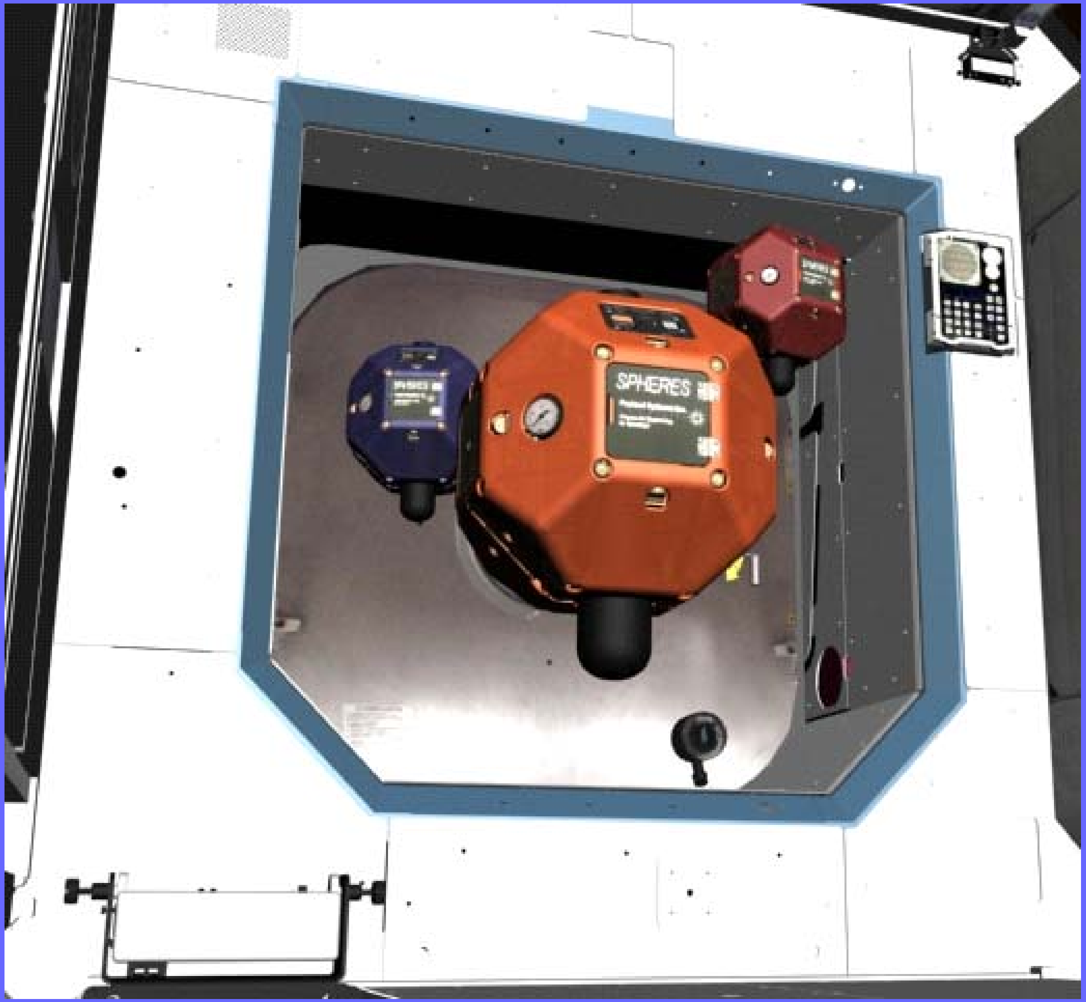
Experimental preview, post-flight visualization



- 3D CAD-based visualization developed at SSRL
- Experimental preview for astronaut
- Post-flight data visualization for scientific analysis

Snapshot from 3D interactive dynamic visualization of 3-SPHERES experiment conducted in US Lab of ISS

Conclusions

- Algorithms for motion-based thruster FDI and mass-property ID
  - Maximum-likelihood-based thruster FDI
  - 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 applied to 4 vehicles in simulation, developing in hardware for SPHERES and S4
- KC flight data validates implementation, on-board gyro filtering issues.
- Future work:
  - Further algorithm and experimental optimization to continue for flight tests aboard ISS in 2004.
  - Hoping to pursue control reconfiguration experiments

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