MCRLS for on-line spacecraft mass- and thruster-property identification

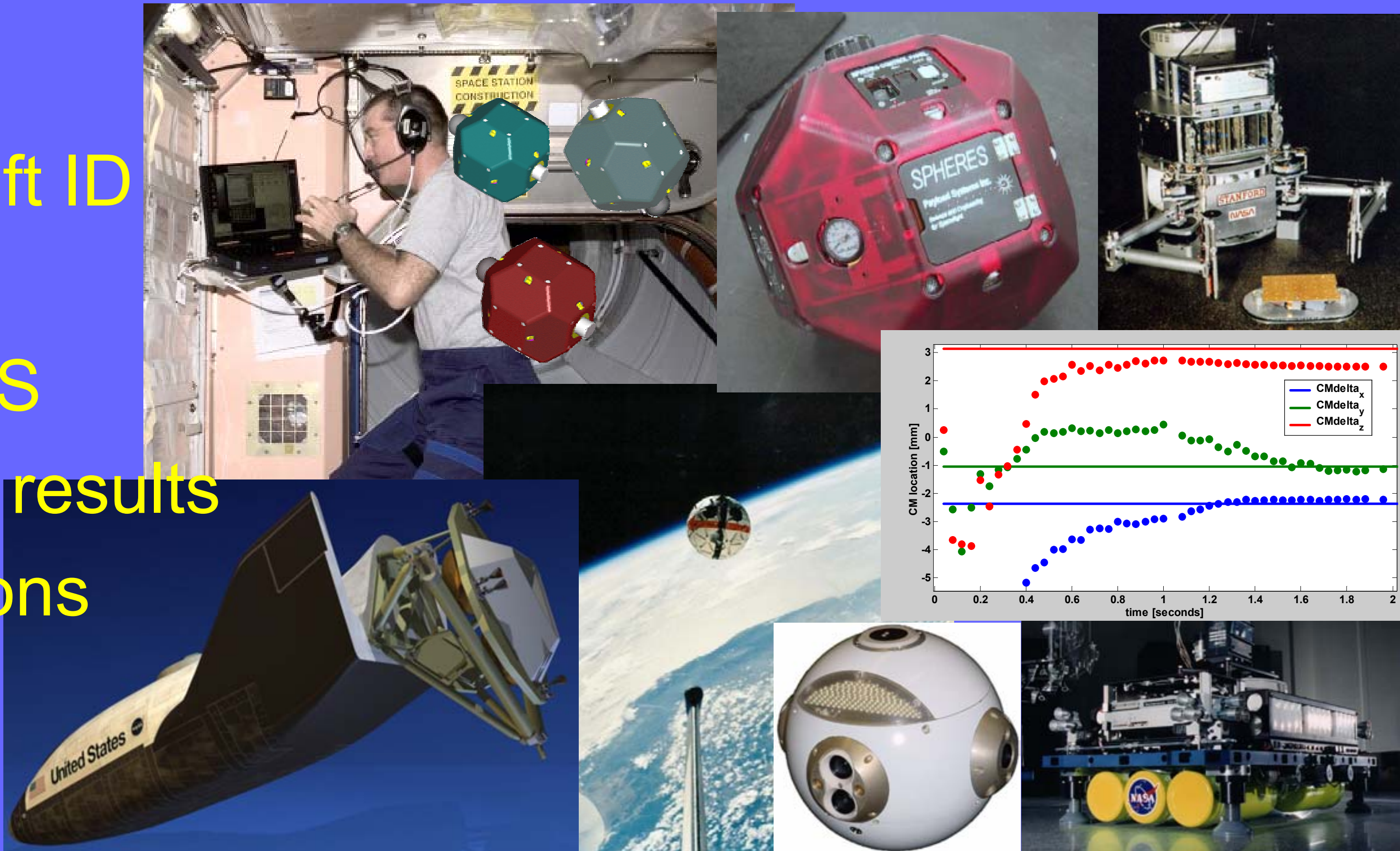
Ed.Wilson@intellization.com
Dave.Sutter@intellization.com
Robert.W.Mah@nasa.gov

Intellization / NASA Ames Research Center
Moffett Field, California, USA

Research objective: For thruster-controlled spacecraft, **identify mass- and thruster- properties** (I, CM, …) using gyros, under normal vehicle control. Applicable for advanced control, estimation, or FDI. Develop and validate through application on realistic simulations and hardware. Flight test on SPHERES aboard ISS in 2005.

Outline:

- Spacecraft ID
- MCRLS
- SPHERES
- KC-135A results
- Conclusions



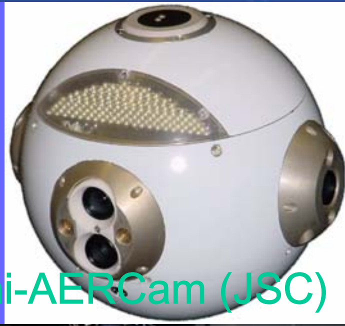
Spacecraft on-line identification (ID)

- **Why** we want to ID mass and thruster properties on-line:
  - Advanced control, estimation, fault detection and isolation (FDI)
  - Fuel consumption, variable payload, variable configuration
  - Small disturbances in space ➔ accurate knowledge is important
- **ID Technologies** for thruster-controlled spacecraft:
  - Small disturbances in space ➔ motion-based (**gyros** are sufficient) analysis is possible, and often more accurate than ground testing
  - **ID:** center of mass (CM) location; inertia matrix; inverse inertia matrix; thruster strength; total mass. Gyros only, gyros+accels (or other sensors).
  - Also - **Thruster Fault Detection and Isolation** (FDI)
  - Generic technologies developed through application to specific problem statements provided by NASA 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 2005

Mass- and thruster-property ID

- Problem statement:
  - For a thruster-controlled spacecraft, with relatively low rotation rates, realistic sensor noise models, realistic thrust variability, using gyros only
  - ID mass and thruster properties
- Principal challenge:
  - Unknown parameters 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) – Second order filter
  - Wilson and Rock (1994) – RLS combined thruster/mass ID; used for on-line neural-network control reconfiguration following multiple thruster failures


X-38 (NASA JSC)


Mini-AERCam (JSC)


S4 (NASA Ames)


SPHERES (MIT SSL)

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, using **Multiple Concurrent Recursive Least Squares (MCRLS)** algorithm
- Separate RLS IDs for CM, inertia, inverse-inertia, thruster strength, …

Center-of-mass 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:

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

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

$$c_k \equiv D(F_{nom} + \hat{F}_{bias})T_k$$

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

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

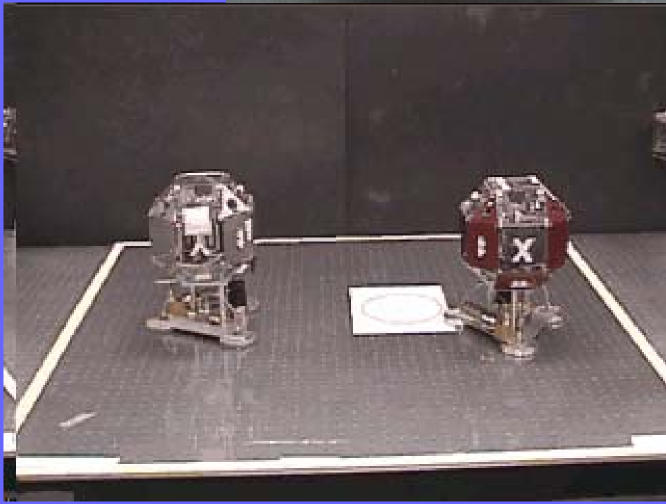
Other derivations listed in paper

- CM ID using gyros and accelerometers
- Inverse inertia ID using gyros
- Inertia ID using gyros, gyroscopic term as disturbance
- Inertia ID using gyros, gyroscopic term treated directly
- Thruster magnitude ID using gyros / accels / both
- Total mass ID

- Mix and match using MCRLS as needed by application

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]



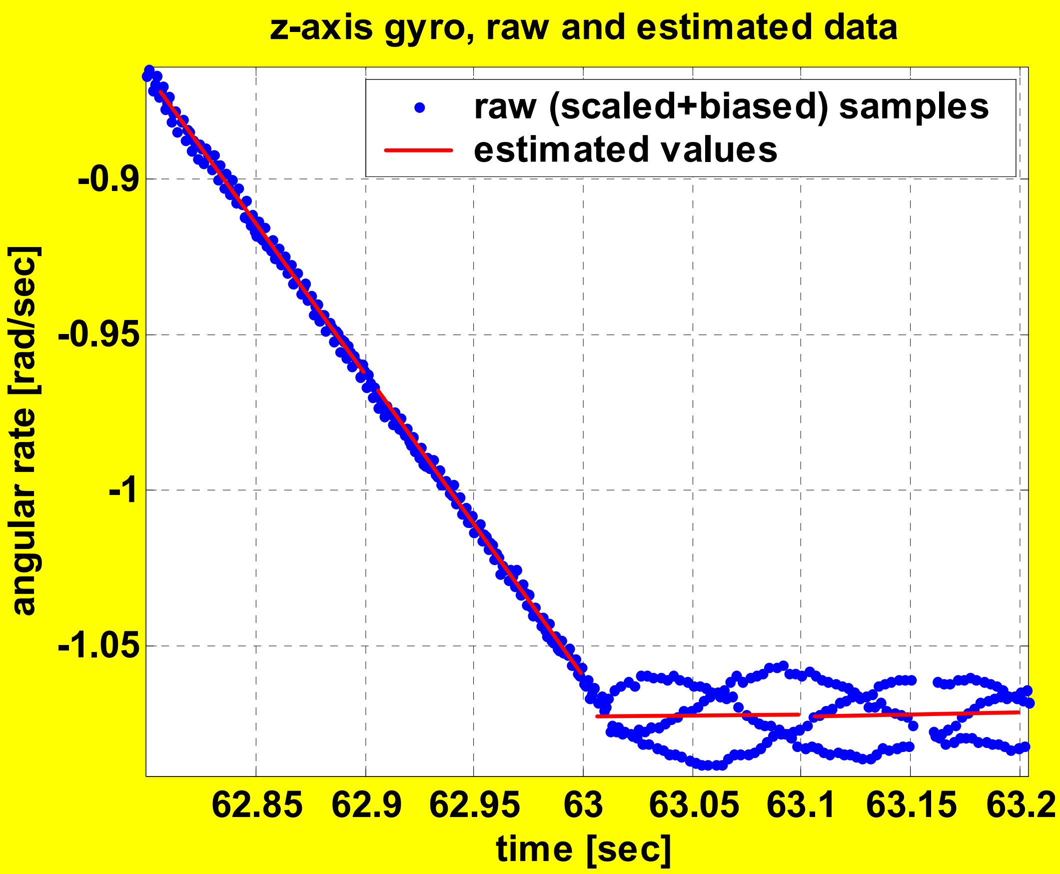
SPHERES properties

- 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 thruster 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.

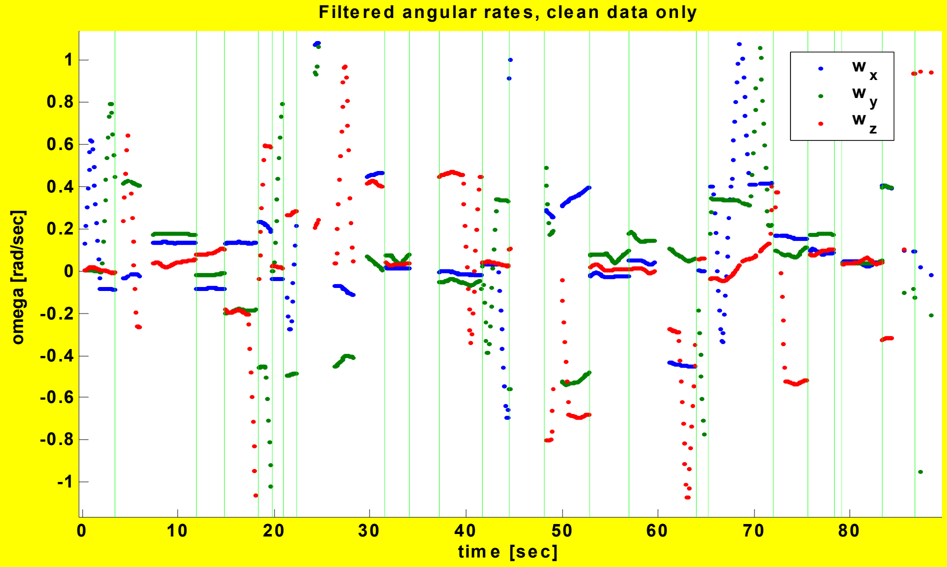
Acceleration estimation performance

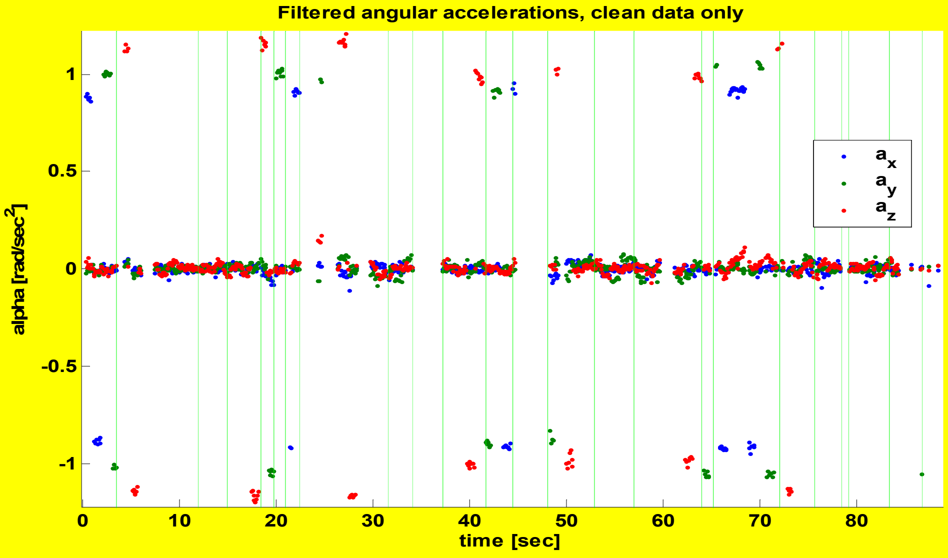


Estimated segment accelerations:
-0.9665 -0.9773 0.0133 0.0167

- 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
- Estimation algorithm in paper

Angular rates and accelerations from on-board filtering

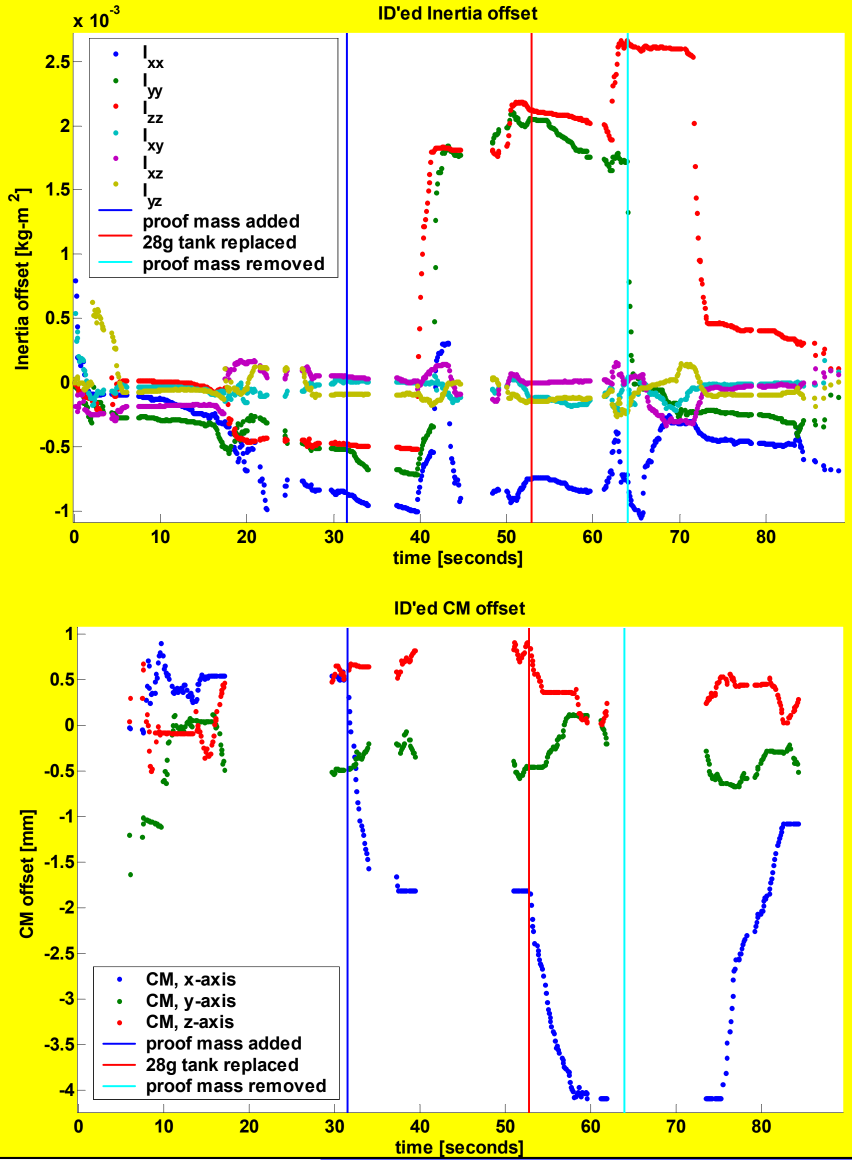

Filtered angular rates, clean data only


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

Intellization
INTELLIGENT SYSTEMS FOR OPTIMIZATION

Inertia and CM ID results

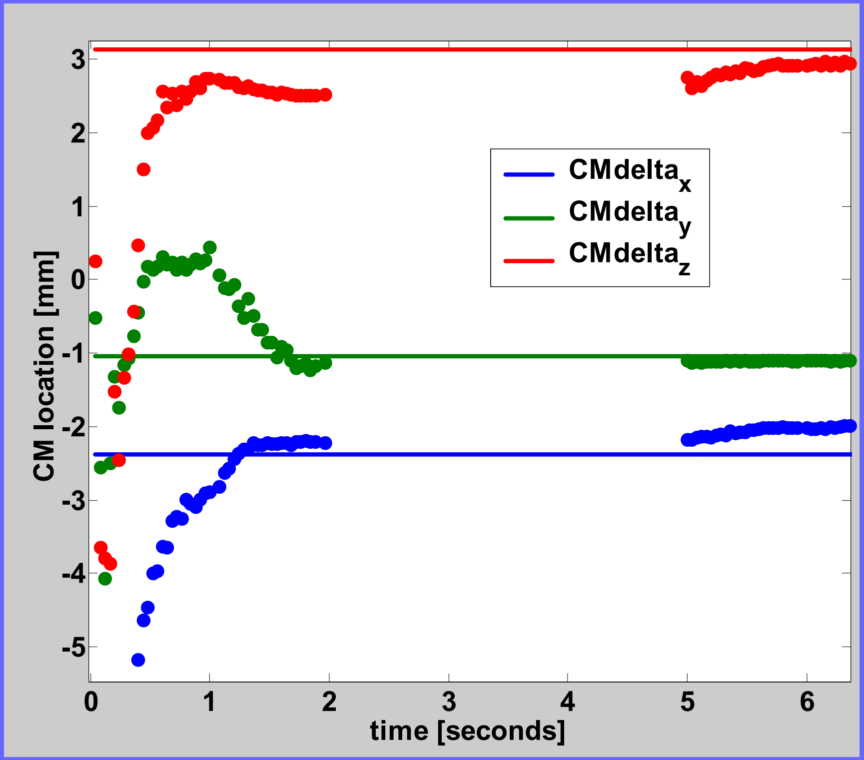


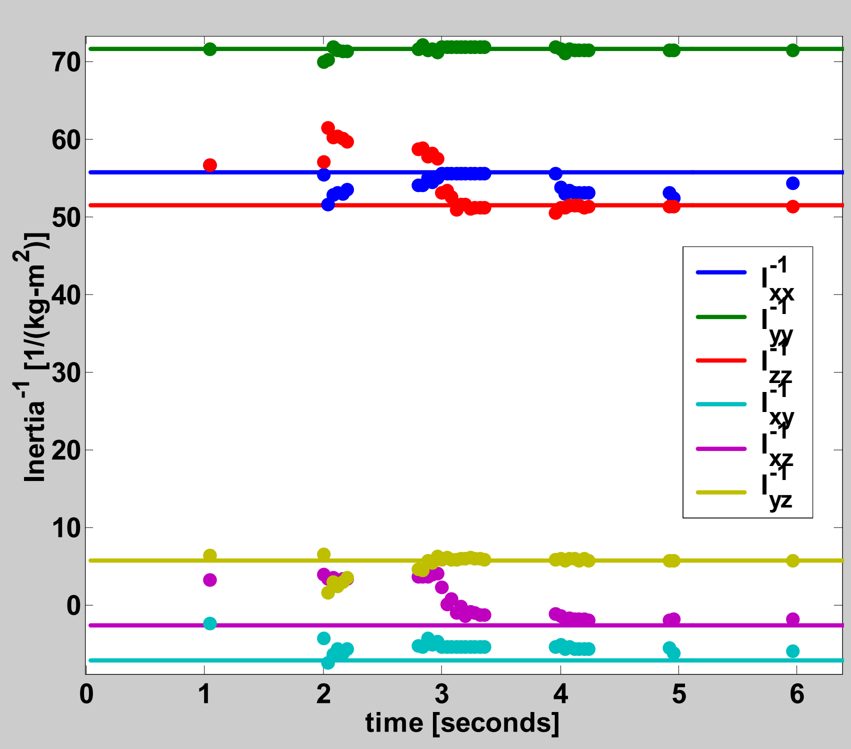
- Proof mass added, removed, near-empty tank replaced
- Fast response indicates feasibility for spacecraft with variable payload or internal reconfiguration
- Certain sections off apparent convergence are actually periods of little excitation
- Meaningful numerical results will require more data, resolution 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

Intellization
INTELLIGENT SYSTEMS FOR OPTIMIZATION

Simulation results

- Accuracy depends on sensor noise, thruster variability, variability in non-ID'ed parameters.
- Applied to 4 vehicles (X-38, Mini-AERCam, S4, SPHERES) in simulation, applied in hardware on SPHERES.





- More accurate than ground analysis/meas. (Mini-AERCam)

Conclusions

- Algorithms presented provide mass-property ID for thruster-controlled spacecraft
- Application of the more generic MCRLS algorithm
- Non-invasive – uses existing sensors, no special motions required, software solution (on- or off-board)
- Generic algorithm - applied to 4 vehicles
- Useful for adaptive control, FDI, especially applicable to vehicles with changing payload, fuel mass, configuration

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

Acknowledgements

- Funded by NASA Headquarters, HQ AA, PWC 349-00: William Readdy and Gary Martin; Presently funded by NASA Intelligent Systems Program (CICT)
- X-38 and Mini-AERCam problem definitions from NASA JSC: Rodolfo Gonzalez, Dr. Steven Fredrickson, Tim Straube, Dave Hammen
- MIT/PSI SPHERES team: Prof. David W. Miller, Dr. Edmund Kong, Dustin Berkovitz, Simon Nolet, Steve Sell (PSI)