Federal Aviation
Administration

COE CST Second Annual Technical Meeting:

Task 244: AR&D for Space Debris Mitigation

Prof. Steve Rock (PI)
Stanford University

1 November 2012

Team Members

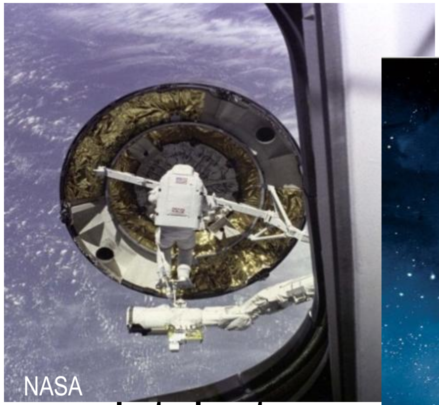
- Prof. Steve Rock (PI)
- Jose Padial
- Marcus Hammond
- Andrew Smith

The Aerospace Robotics Lab

Department of Aero and Astro

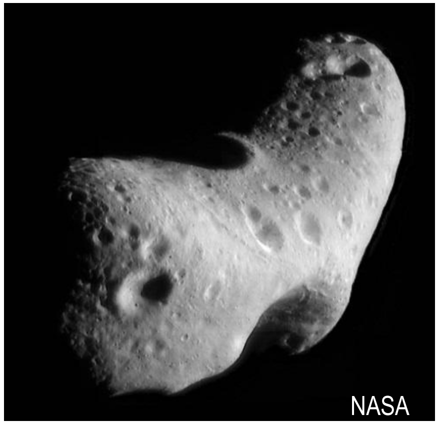
Stanford University

Motivation and Background



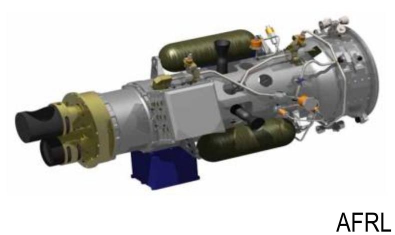
Intelsat

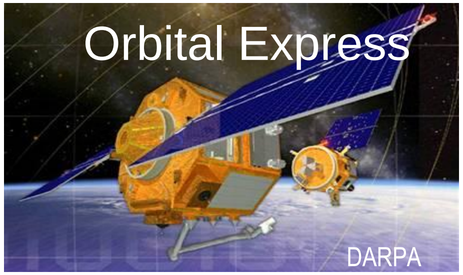
DSP-2

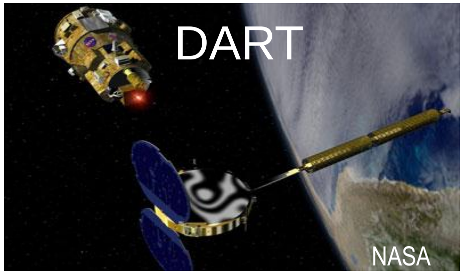


Related Missions

XSS



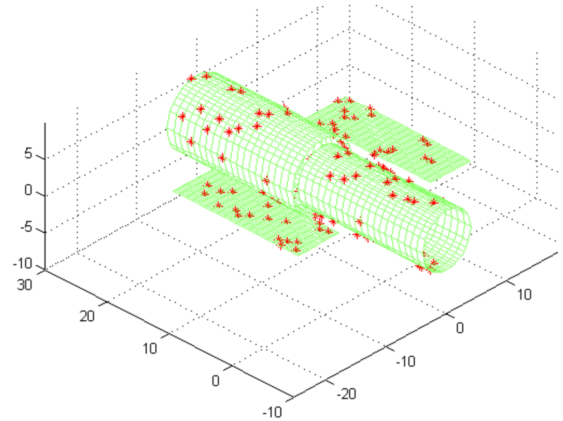




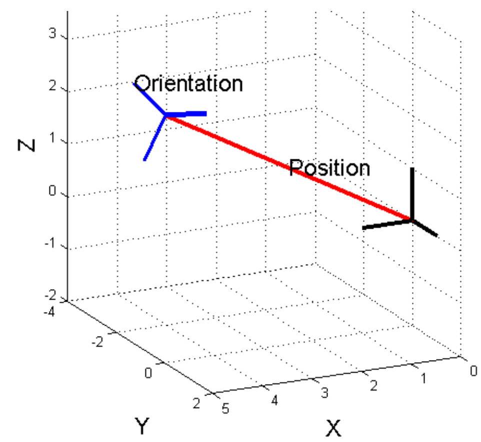
Statement of Purpose

- **Target Reconstruction and Pose Estimation**
- **Unstructured rendezvous situations**
  - **Tumbling target motion**
  - **No a priori information**
  - **Uncommunicative target**
- **Enable this capability on a nano-satellite observer**
  - **Small satellites impose sensing constraints**

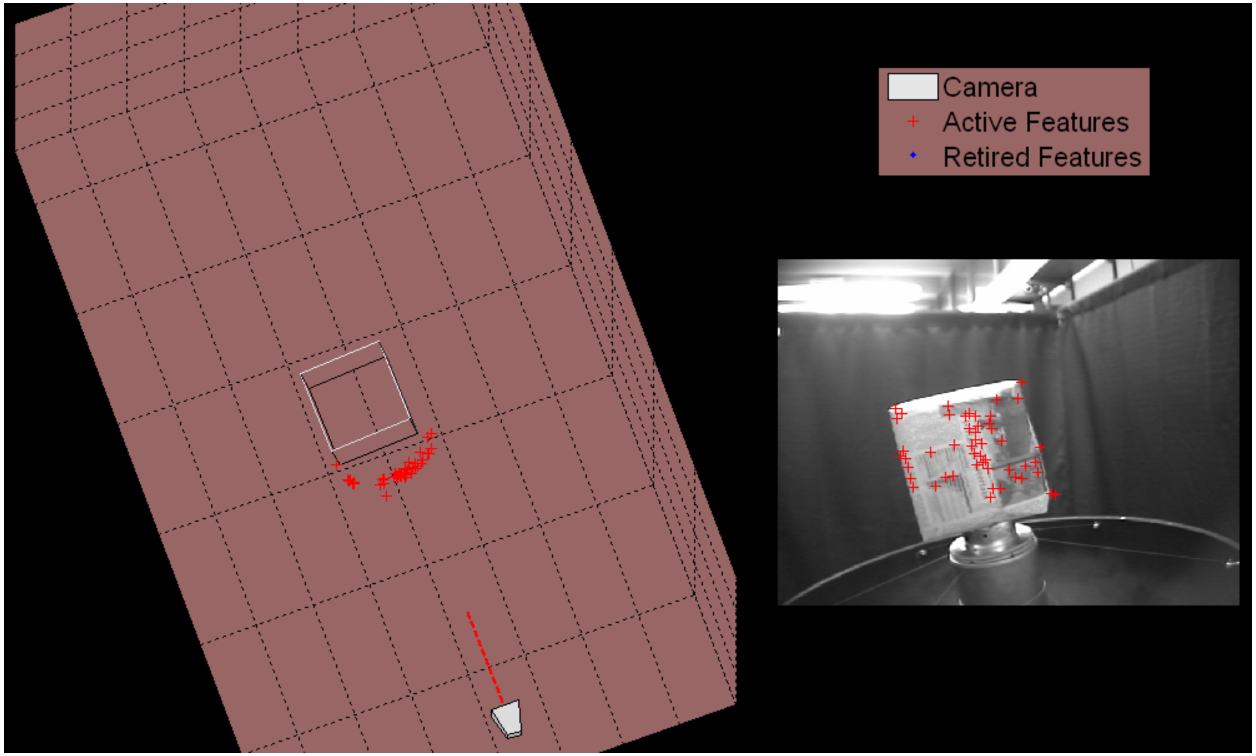
Target Reconstruction



Target Pose



Monocular Vision Tracking



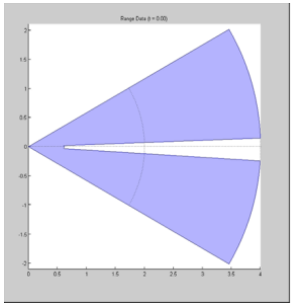
- Scale Ambiguity
- Sparse Reconstruction

→ **Add Range Sensing**

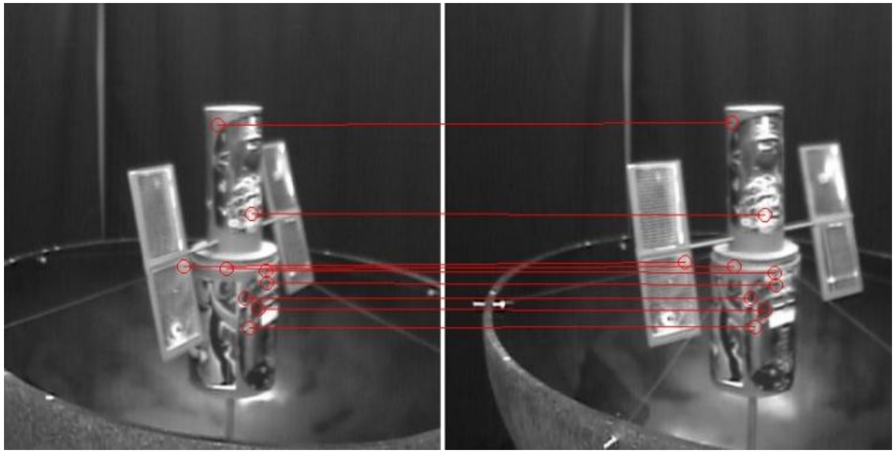
S. Augenstein and S.M. Rock. *Improved Frame-to-Frame Pose Tracking during Vision-Only SLAM/SfM with a Tumbling Target.* ICRA, 2011.

Fusion of Vision and Range Data

- Sparse-pattern Range Data
  - Line-scanning Laser
  - Low-resolution Flash LIDAR

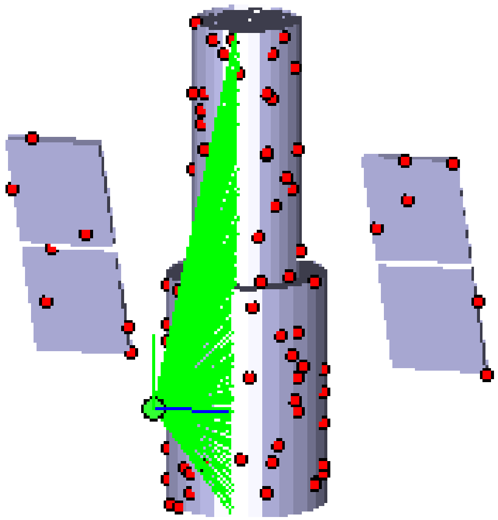


- Range data incapable of providing frame-to-frame correspondence
- Visual feature tracking (SIFT) used for frame-to-frame correspondence



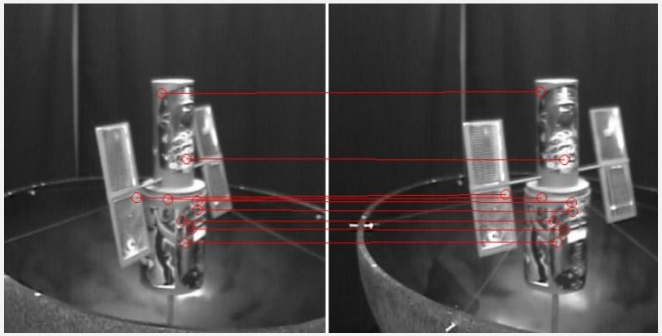
Fusion of Vision and Range Data

- **Monocular vision enables target reconstruction and pose estimation, but scale factor is unknown**
- **Scanning range data enables scale factor determination, but is subject to data smearing**
- **Challenge: alignment of disparate and sparse point clouds**



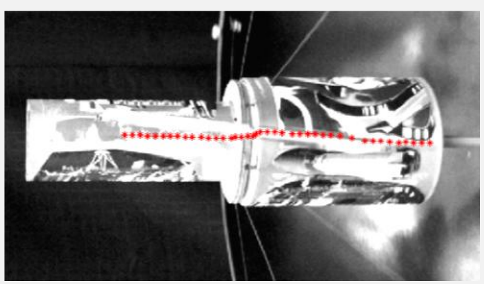
Algorithm Overview

Frame-to-Frame Vision Correspondence



Incorporate Range Returns

- Project range returns onto images
- Determine vision-range correspondence



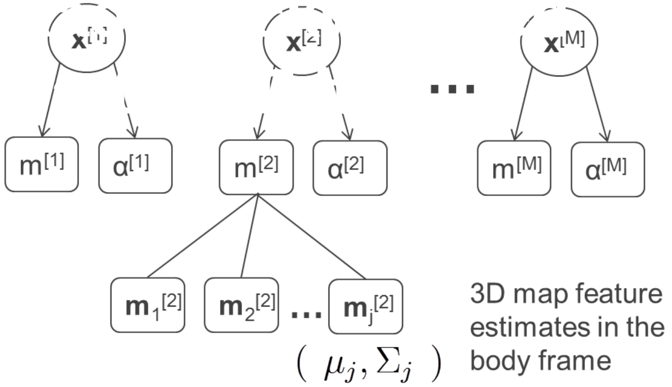
Rao-Blackwellised Particle Filter Framework

- Visual feature tracking drives particle weighting
- Vision-range correspondence for scale factor estimation

Pose Estimates

Target Map

Algorithm Details



Details of the algorithm in:

J.Padial, M.Hammond, S.Augentstein, and S.M.Rock, “Tumbling Target Reconstruction and Pose Estimation through Fusion of Monocular Vision and Sparse-Pattern Range Data”, *IEEE International Conference on Multisensor Fusion and Information Integration (MFI)*: IEEE Press, 2012.

And/or discuss with Jose by poster!

2D Vision Feature Measurements

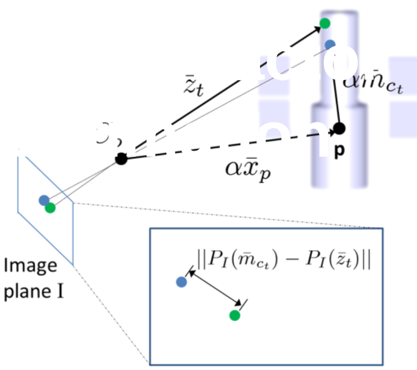
$$y_i^t = [u_i, v_i]_t^T$$

Expected Vision Measurements

$$\hat{y}_j^{t|i} = K(R_t^{[i]} \mu_j^{[i]} + \bar{x}_{p,t}^{[i]})$$

Particle Weighting

$$w^{[i]} = \prod_{j=1}^{N} \frac{1}{|2\pi\Sigma_j^{[i]}|^{0.5}} e^{-\frac{1}{2}||y_j^t - \hat{y}_j^{t\,[i]}||^2_{\Sigma_j^{[i]}}}$$



Vision-range Correspondence

$$\hat{c}_t = \arg\min_{c_t} \; ||P_I(\bar{m}_{c_t}) - P_I(\bar{z}_t)||$$

$$\text{subject to } ||P_I(\bar{m}_{c_t}) - P_I(\bar{z}_t)|| \leq \beta$$

Scale Estimation System is *Linear*

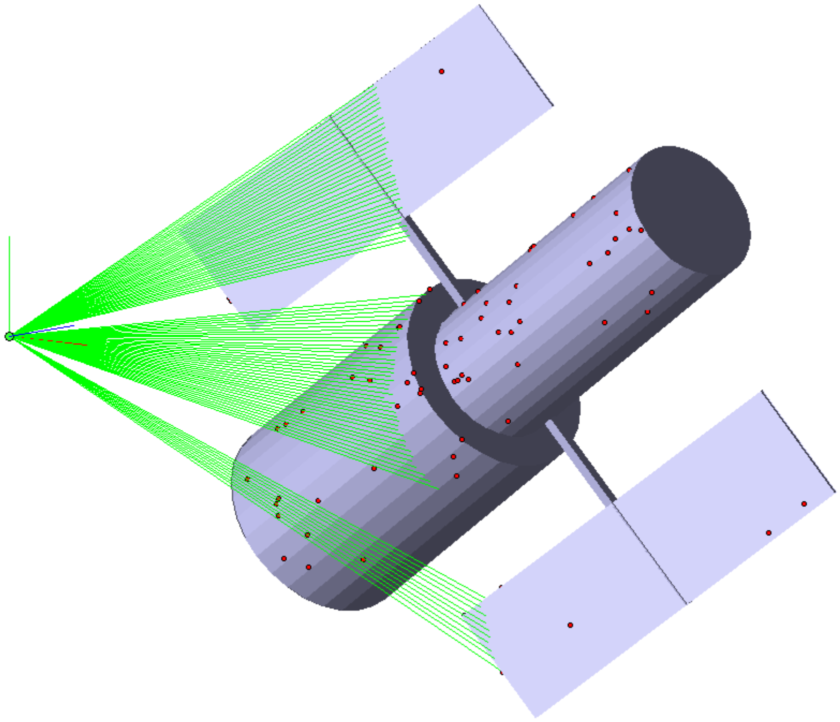
$$\bar{z}_t = (\, R(\bar{\theta}_t)^{B/C} \bar{x}_{p,t} + \bar{m}_{\hat{c}_t})\alpha_t + \bar{\delta}_z$$

$$\bar{\delta}_z \sim \mathcal{N}(0, \Gamma_{z_t})$$

Gaussian Measurement Distribution is *Linear* in Scale

$$p(z_t|\alpha_t, x^t, z^{t-1}, c^t) \sim \mathcal{N}(\, z_t;\; (R(\bar{\theta}_t)^{B/C}\bar{x}_{p,t} + \bar{m}_{\hat{c}_t})\alpha_t,\; \Gamma_{z_t} + \alpha_t^2 \Sigma_{\hat{c}_t})$$

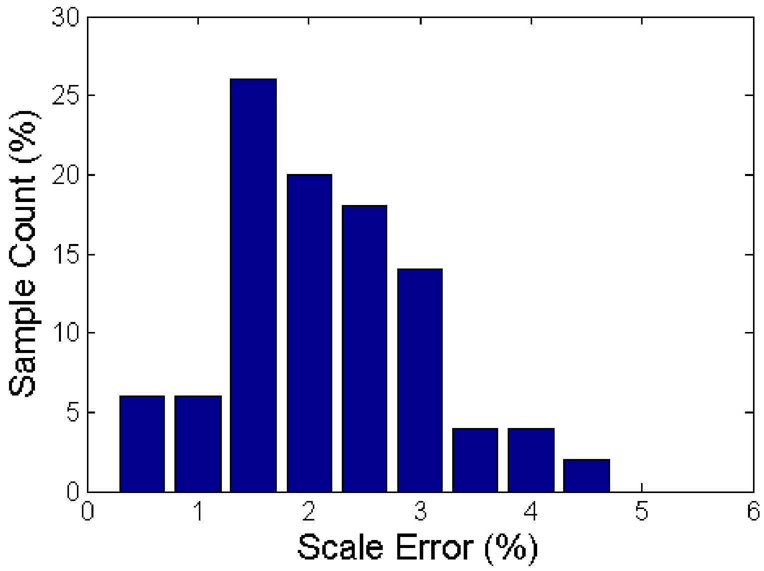
Simulation Environment

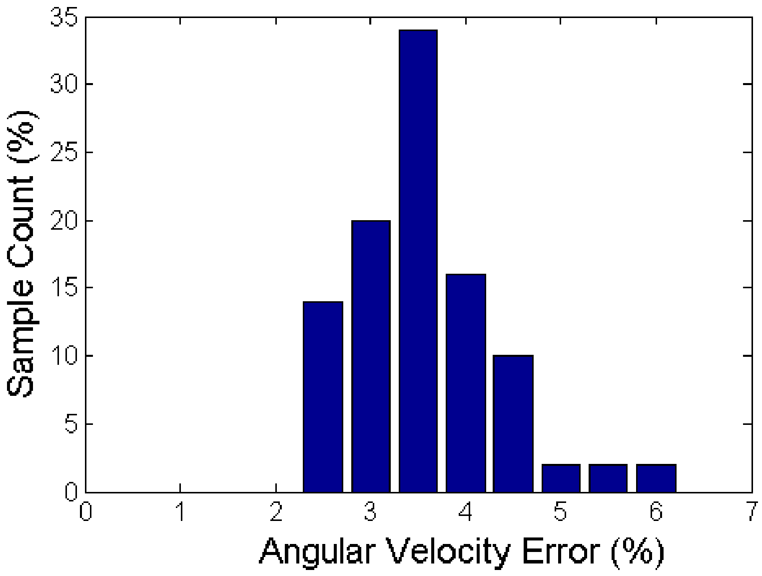


- **Target and observer (point-mass)**
- **Relative motion profile simulated**
- **Pixel measurement noise**
  - **sampled from zero-mean Gaussian with 1-pixel variances**
- **Range measurement noise**
  - **sampled from a zero-mean Gaussian with standard deviation 1% true DT**

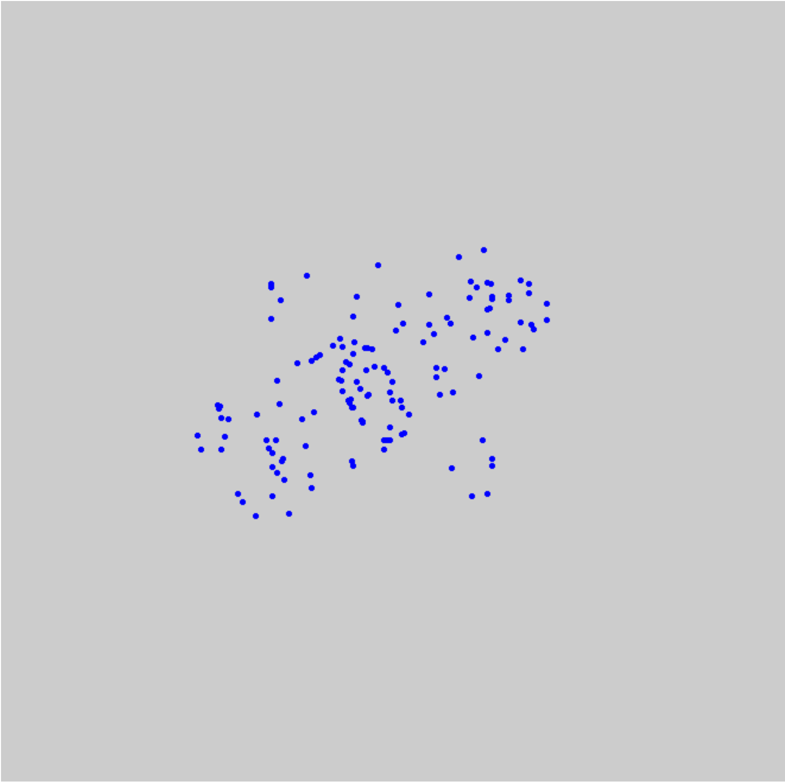
Simulation Results

Estimate Error	Mean	Std. Deviation	Max
Scale	2.14%	0.86%	4.36%
Angular Velocity	3.62%	0.71%	5.77%

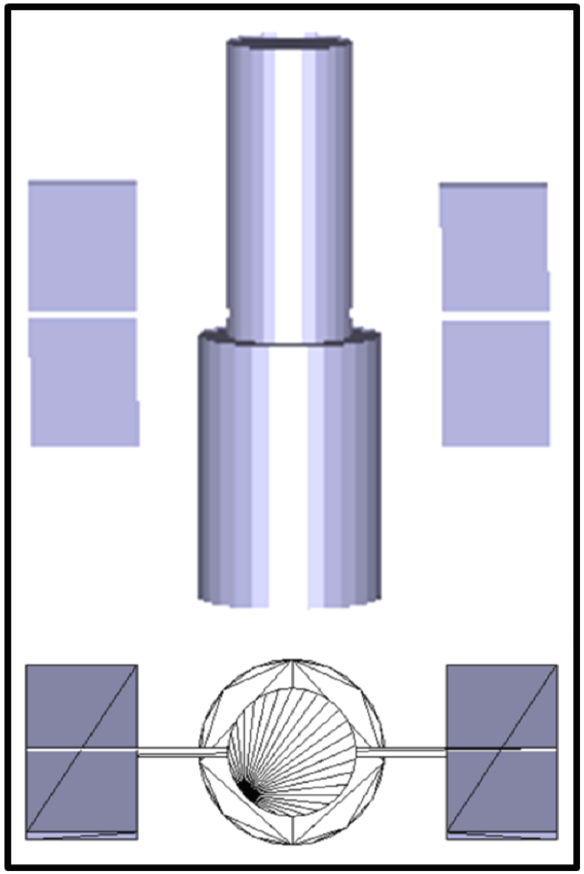




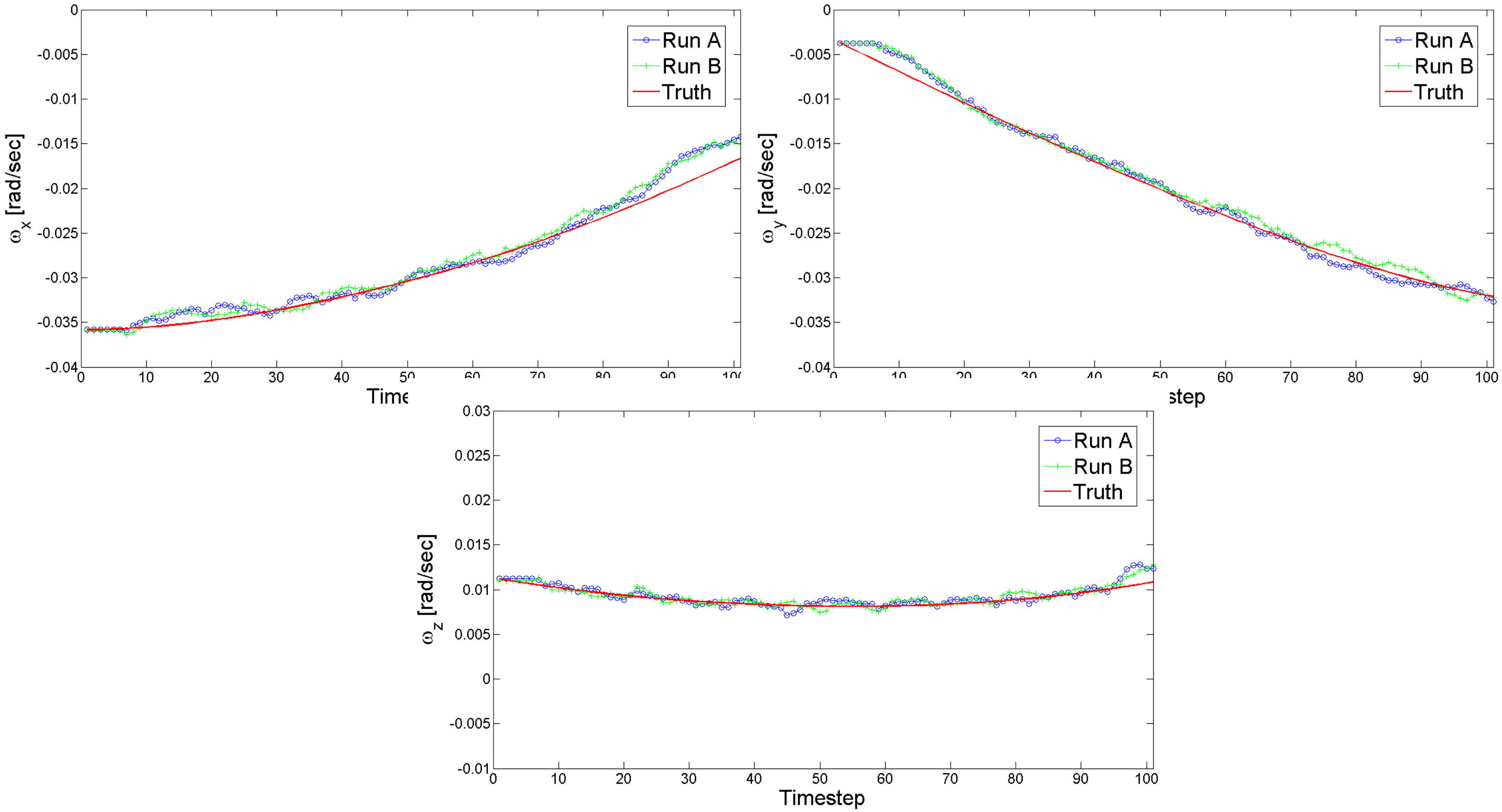
Simulation Results



Run A: 0.42% scale error,
3.42% angular velocity error



Simulation Results - Angular Rate Tracking

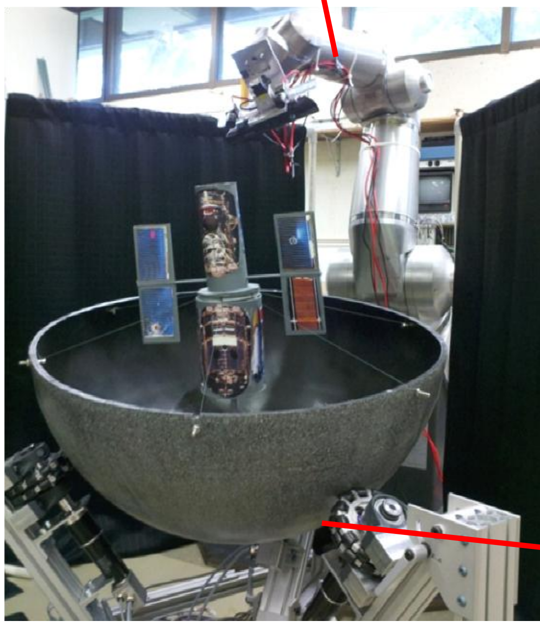


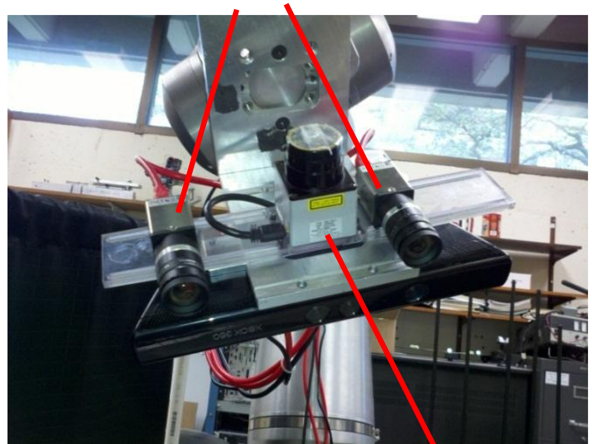
Hardware Test Platform

R^2 manipulator arm

Camera

Motion Capture IR Cameras



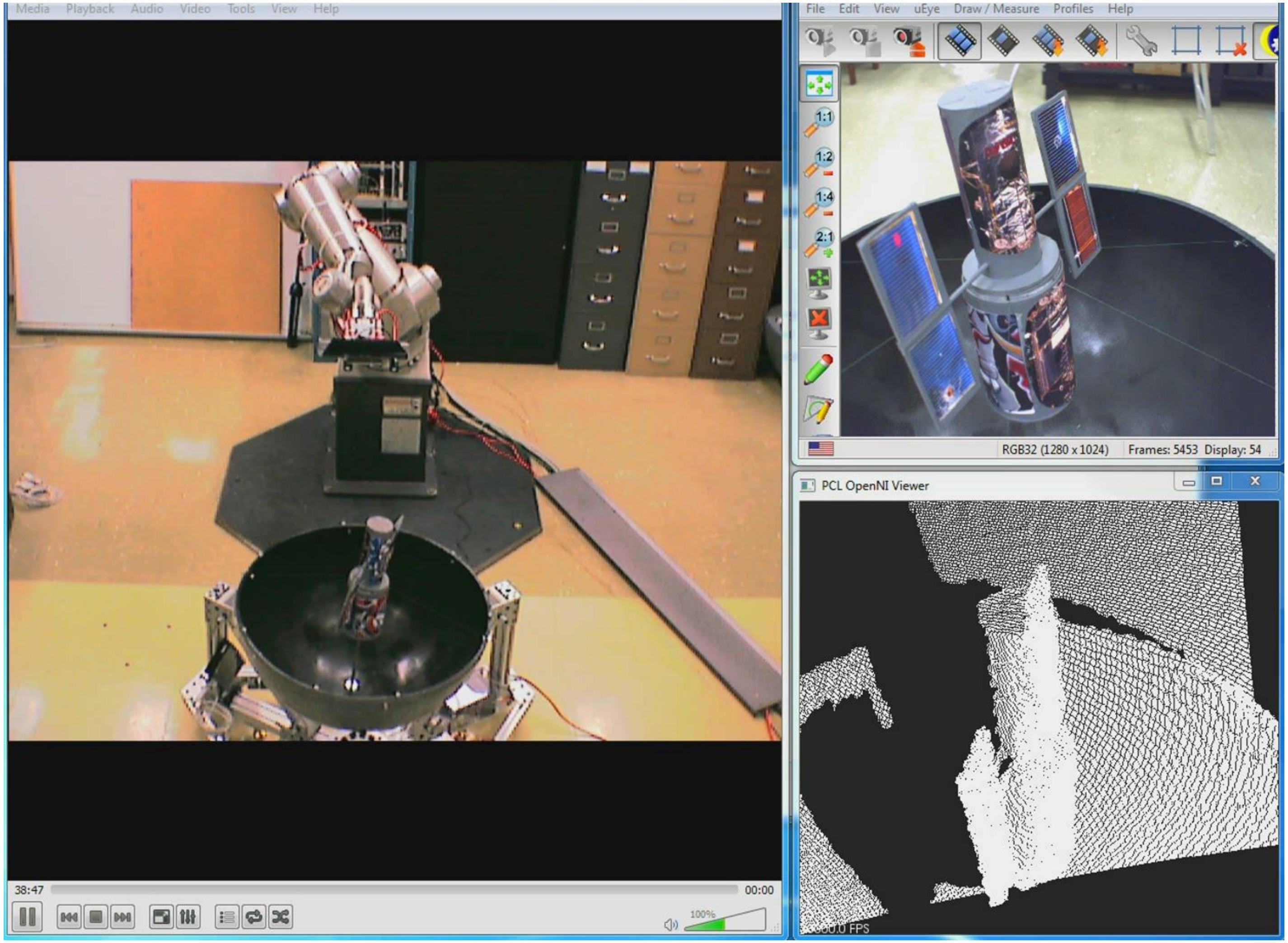


Line-scanning laser range finder

Tumbling base motion simulator

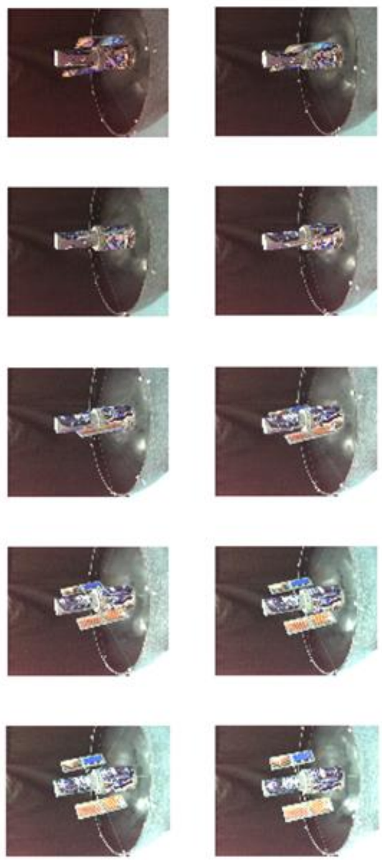
- **Simulink-based manipulator and tumbling base control with synchronized camera/ranging data collection and IR truth data collection**

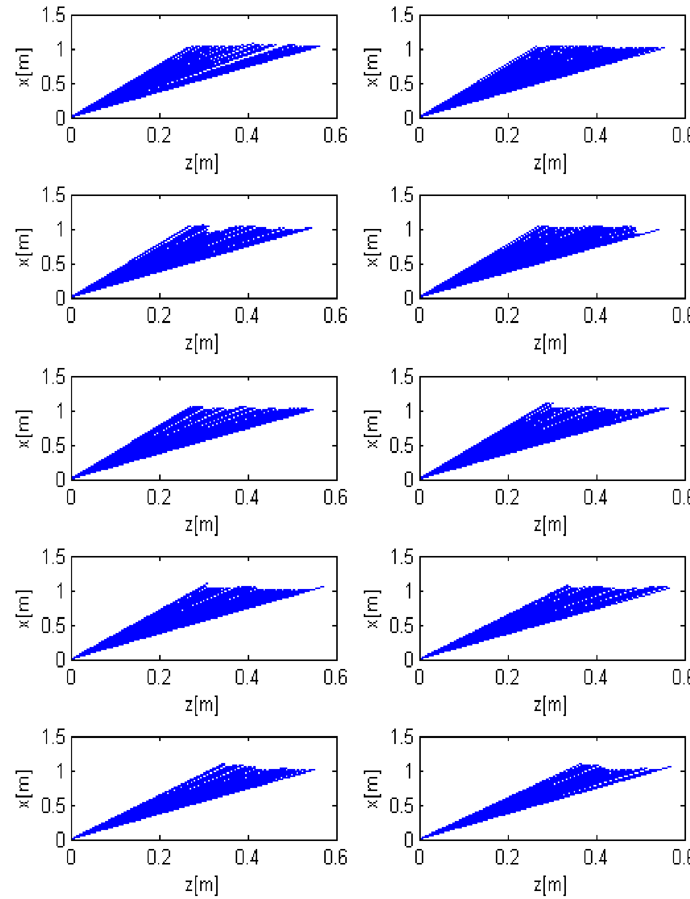
Hardware Test Platform



Hardware Data Collected

10 sample images and laser range finder scans from dataset collected with ARL hardware test platform.





Moving Forward

In Progress:

- Initial hardware experimental data generated
- Dealing with truth data synchronization issues
- Dealing with algorithmic bugs in processing data

Priorities Moving Forward:

- Complete testing in ground-based hardware simulator
- Extend simulation studies and algorithmic analysis
  - Varying target geometries
  - Varying relative motion trajectories
- Modify algorithms to enable deployment on flight hardware (e.g. small sats)

TASK 244: AUTONOMOUS RENDEZVOUS AND DOCKING (FOR SPACE DEBRIS MITIGATION - TARGET POSE & SHAPE SENSING)

PROJECT AT-A-GLANCE

- AST RDAB POC: Nick Demidovich
- AST RESEARCH AREA: 2.3 Vehicle Safety Systems & Technologies
- UNIVERSITY: Stanford University
- PRINCIPAL INVESTIGATOR: Dr. Steve Rock
- STUDENT RESEARCHER: Jose Padial (PhD), Marcus Hammond (PhD), Andrew Smith (PhD)
- PERIOD OF PERF: Jan 1, 2011 – May 2013
- STATUS: Ongoing

RELEVANCE TO COMMERCIAL SPACE INDUSTRY

- Safe approach and successful capture of uncooperative space debris will require the ability to autonomously identify the object of interest and its motion vectors.

STATEMENT OF WORK

- Develop and demonstrate robust autonomous rendezvous and docking (AR&D) sensing technology for
  - Targets undergoing complex, potentially tumbling motion
  - Damaged and/or uncommunicative spacecraft
  - Orbital debris.
- Develop new technology to enable safe, autonomous rendezvous and docking with disabled spacecraft or capture of debris

Improved 6DOF ground-based hardware experiment

STATUS

- Camera-LIDAR simulation environment completed
- Fused vision-LIDAR algorithm validated in simulation
- Validation in ground-based experiment

FUTURE WORK

- Complete validation of fused algorithm in ground-based experiemnt
- Modify /extend algorithms for small-sat compatible processors
- Identify and prepare for flight experiment

Contact Information

- Prof. Steve Rock (PI)
- Jose Padial
- Marcus Hammond
- Andrew Smith

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