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Laboratory experimental validation of autonomous spacecraft proximity maneuvers

Prof. Marcello Romano

Mechanical & Astronautical Engineering Department
U.S. Naval Postgraduate School, Monterey, California, USA

mromano@nps.edu

NAVAL POSTGRADUATE SCHOOL

Spacecraft Robotics LABORATORY

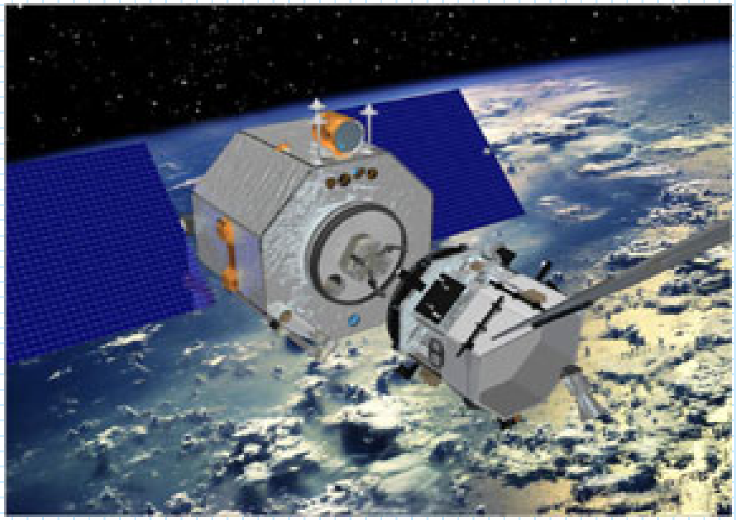
Outline

1. Tasks and motivation
2. The Spacecraft Proximity Operations Facility
3. The 1st-generation spacecraft simulators
4. The 2nd-generation spacecraft simulators
5. Conclusions

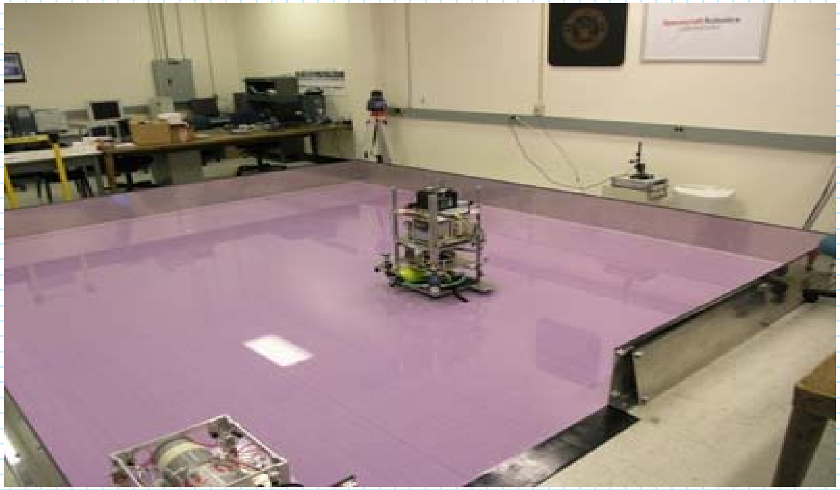
Task and rationale of the on-going Researches

Design and build a Hardware-In-the-Loop test-bed to validate GN&C algorithms for the proximity operations of small spacecraft, including autonomous docking and multi-spacecraft assembly

1960-	Russian missions
1997-99	Japan ETS-VII
2001	China-UK Snap 1
2003/05	AFRL XSS-10/11
2005	Nasa DART
2007	*DARPA Orbital Express*
2007	*ATV to ISS*
2010-…	*NASA Project Constellation*

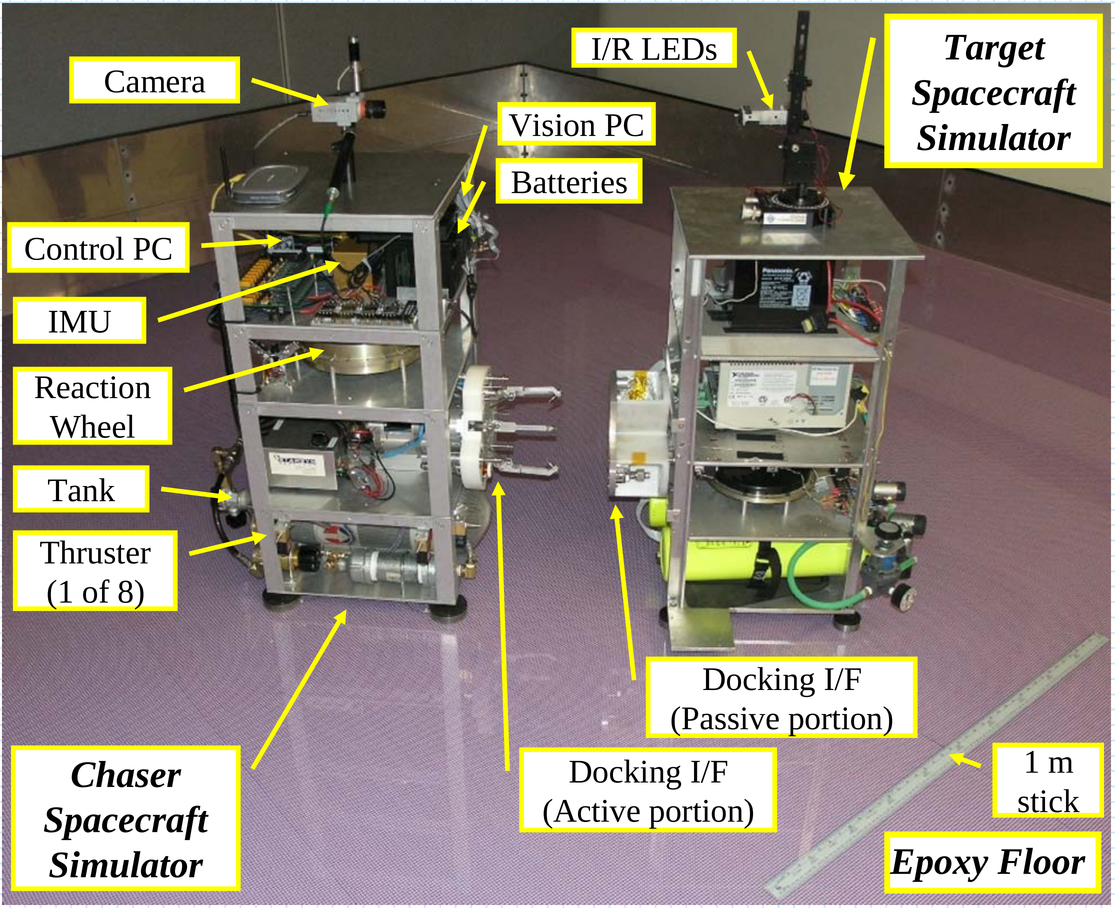


Proximity Operations Facility @ Spacecraft Robotics Lab



- 4.9 m by 4.3 m Epoxy Surface (Residual Gravity: ~10^{-3} g)
- S/C simulators float via air-pads
- Dynamics + Kinematics simulator
  1. Recreates weightlessness and frictionless condition in 2D
  2. Angular/linear momentum conservation respected
  3. Enables validation of Dynamics model and GNC algorithms, while they interact with real actuators/sensors/internal body motion dynamics
  4. Complementary to 3D analytical-numerical simulations & kinematics-only simulation facility

1st-generation Spacecraft Simulators (AUDASS)



Size	Length and Width	0.4 [m]
	Height	0.85 [m]
	Mass	63 [Kg]
	Moment of Inertia about Y_{ch}	2.3 [Kg m^2]
Propulsion	Propellant	Air
	Equivalent Storage Capacity	0.72 [m^3] @ 0.35 [Mpa]
	Operating Pressure, Thrust	0.35 [Mpa] (50 [PSI])
	Operating Pressure, Floating	0.24 [Mpa] (35 [PSI])
	Continuous Operation	20 – 40 [min]
	Thrust of each thrusters	0.45 [N]
	Reaction Wheel Max Torque	0.16 [Nm]
	Reaction Wheel Max Angular Momentum	20.3 [Nms]
Electrical & Electronic Subsystem	Battery Type	Lithium-Ion
	Storage Capacity	12 [Ah] @ 28[V]
	Continuous Operation	~ 6 [h]
	Computers	2 PC104 Pentium III
Sensors	IMU	Crossbow 400CC
	Vision Sensor	custom developed
	CMOS Camera	Pixelink PL-A471
	Camera Field of View	40 [deg]
	Vision Sensor Range	0-10 [m]
Docking I/F Capture Tolerances	Max Axial Misalignment	+/- 7.62 [cm]
	Max Lateral Misalignment	+/- 5.08 [cm]
	Max Angular Misalignment (Pitch, Yaw, Roll)	+/- 5 [deg]

1st-generation simulator: Vision Based Navigation

CMOS Camera

↓

Image Processing

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Distortion Compensation

↓

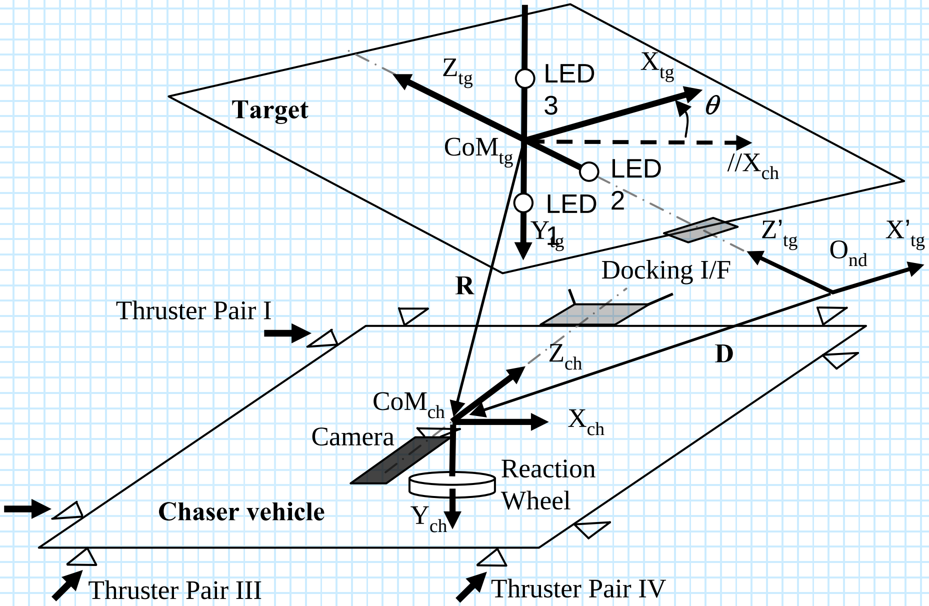
Pinhole Camera Model

↓

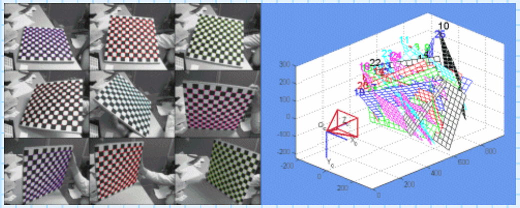
3-Points Based Navigation

↓

R components and θ



Camera intrinsic parameters and distortion coefficients estimated through off-line calibration



Resulting accuracy in position = ~1 mm, in angle = ~0.1 deg

Resulting overall sample frequency = ~5 Hz

1st-generation simulator: Fusing Vision Sensor and IMU Data

- Discrete Kalman Filters implementation for the relative navigation, fusing vision and IMU data

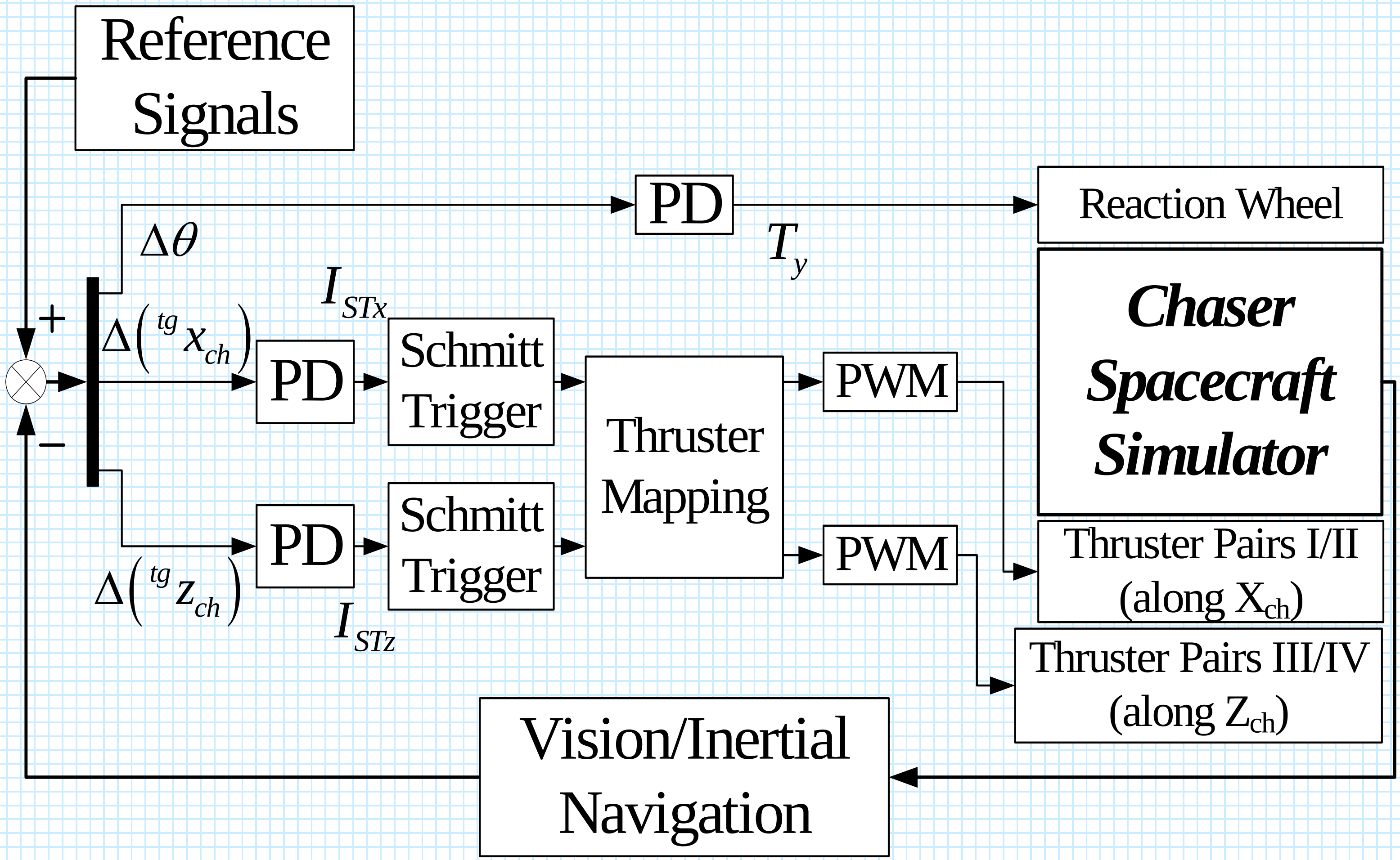
Attitude

$$\begin{cases} \mathbf{x}_k = \begin{bmatrix} \theta_k & \gamma_k \end{bmatrix}^T, \ \mathbf{u}_k = \tilde{\dot{\theta}}_k \\ H_{[k-delay(k)]} = [1 \quad 0], \ \mathbf{v}_{[k-delay(k)]} = \begin{bmatrix} v_{\theta\,cam\,[k-delay(k)]} \end{bmatrix} \end{cases}$$

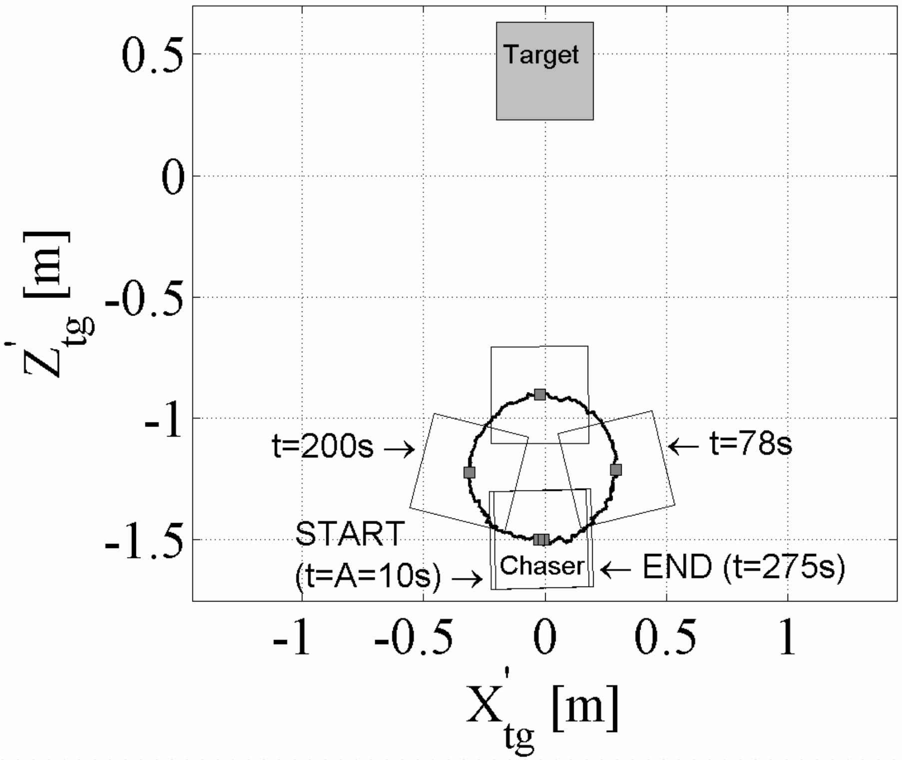
Translation

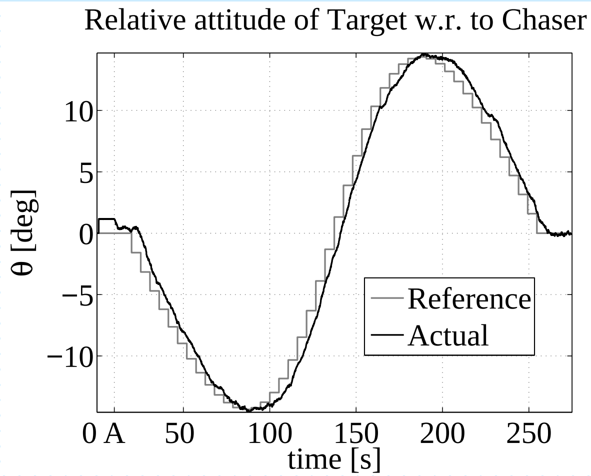
$$\begin{cases} \mathbf{x}_k = \begin{bmatrix} {}^{tg}x_{ch\,k} & {}^{tg}\dot{x}_{ch\,k} & \beta_{x\,k} & {}^{tg}z_{ch\,k} & {}^{tg}\dot{z}_{ch\,k} & \beta_{z\,k} \end{bmatrix}^T \\ \mathbf{u}_k = \begin{bmatrix} \tilde{\ddot{x}}_k & \tilde{\ddot{z}}_k \end{bmatrix}^T \\ H_{[k-delay(k)]} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}, \\ \mathbf{v}_{[k-delay(k)]} = \begin{bmatrix} v_{x\,cam\,[k-delay(k)]} & v_{z\,cam\,[k-delay(k)]} \end{bmatrix}. \end{cases}$$

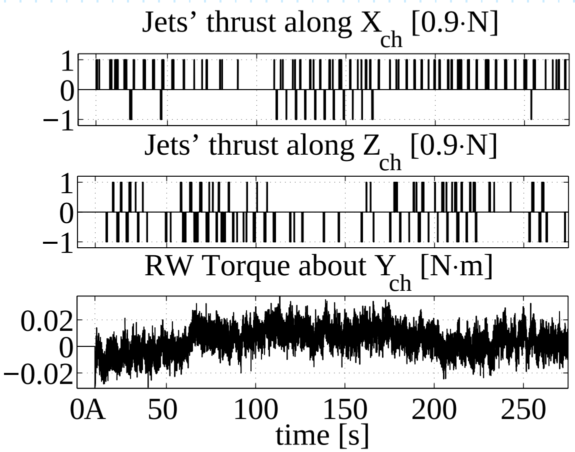
1st-generation simulator: Chaser Spacecraft Control



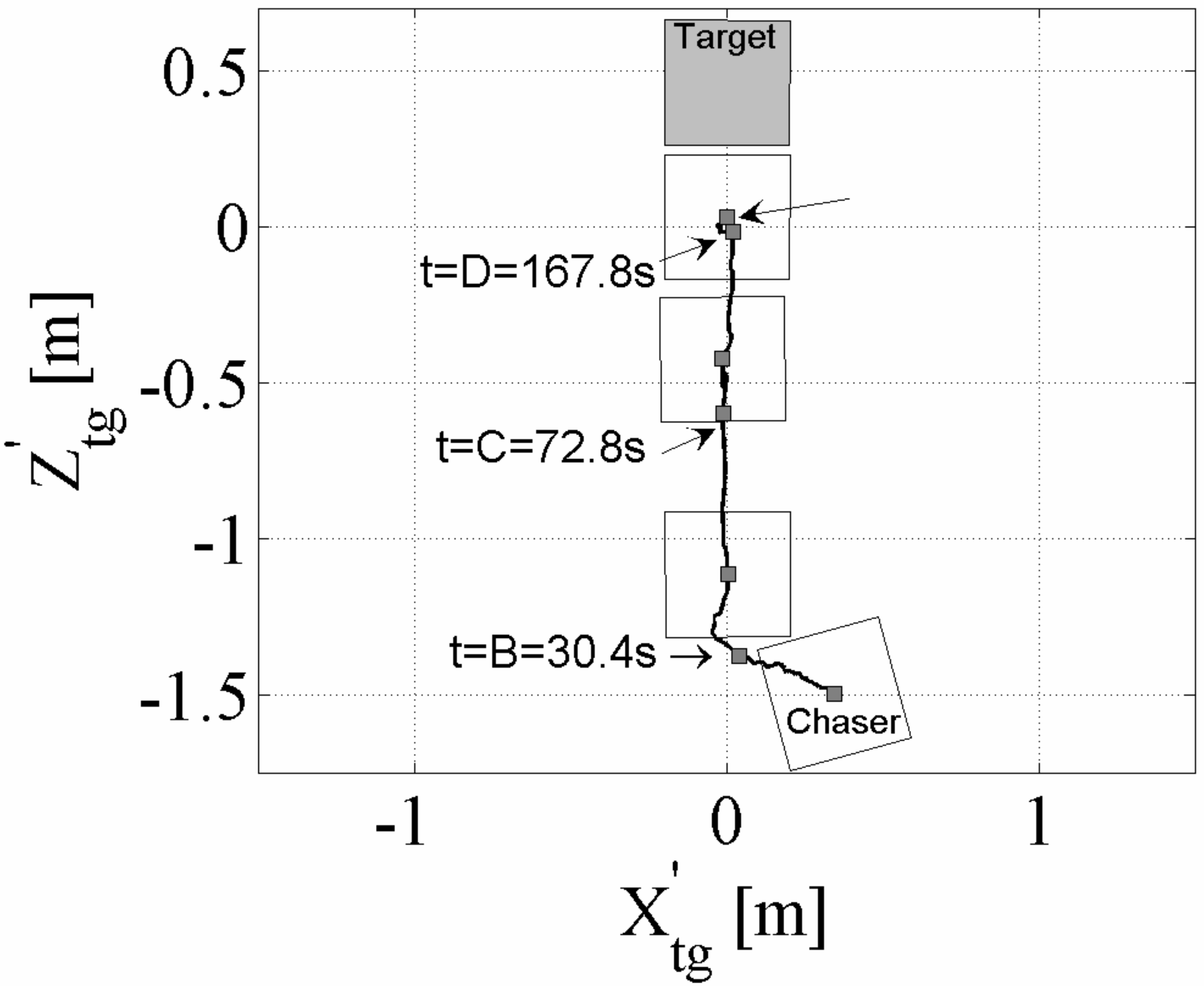
1st-generation simulator: Test 1: Trajectory Tracking





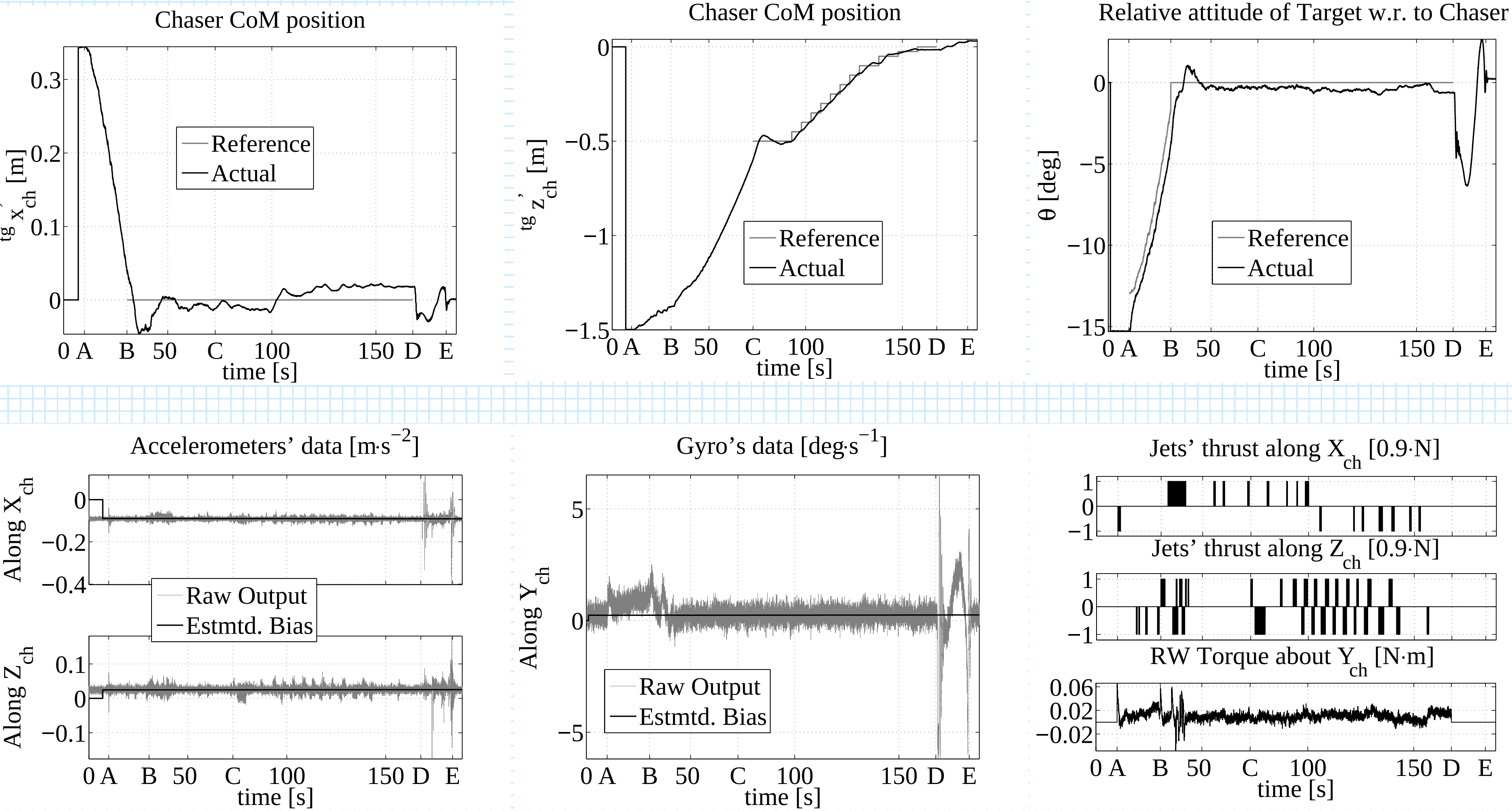


1^{st}-gen. simulator: Test 2: Autonomous Docking Maneuver

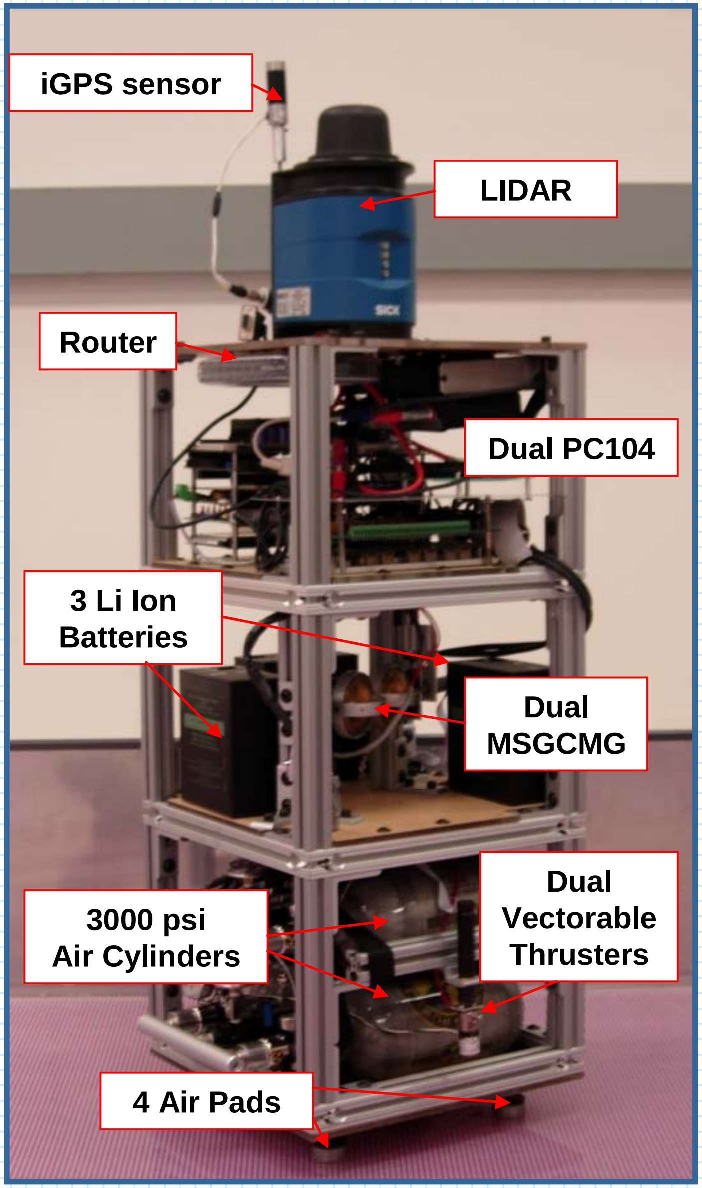


MOVIE

1st-gen. simulator: Test 2: Auto. Docking Maneuver (details)



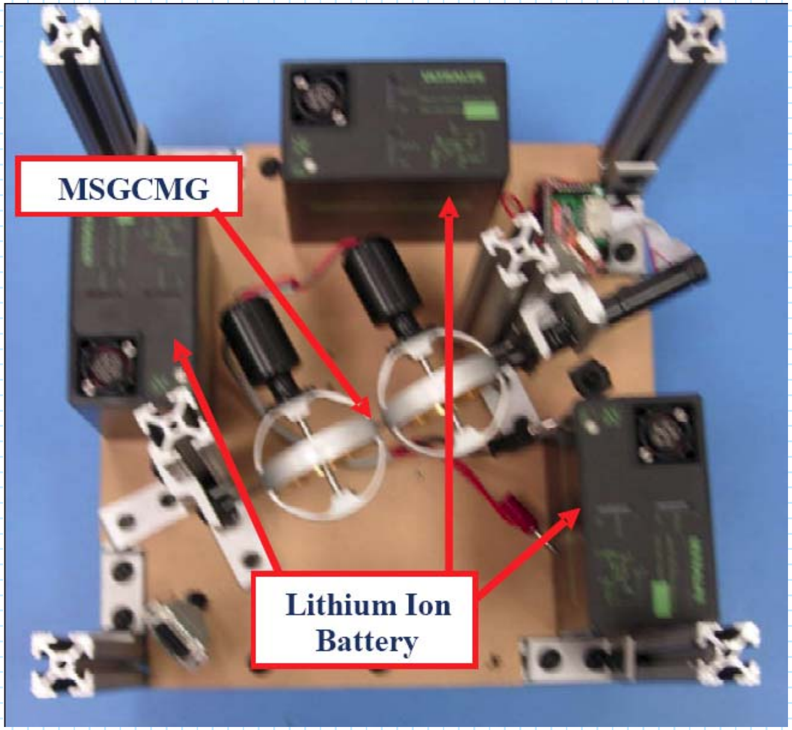
2nd-generation Spacecraft Simulator



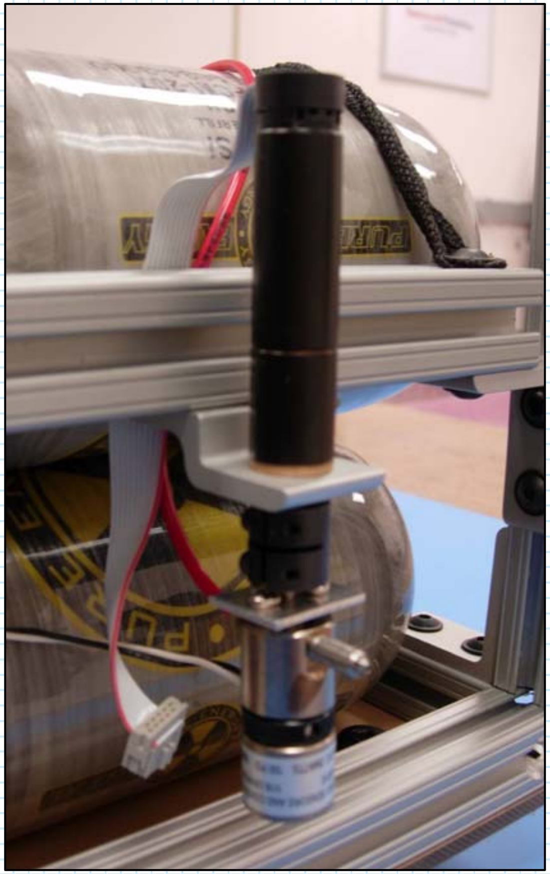
Size	Length and Width	.30 [m]
	Height	.69 [m]
	Mass	37 [kg]
	Moment of Inertia Z_{veh}	.75 [kg m^2]
Propulsion	Propellant	Air
	Equiv Storage Cap @ 21 [MPa] (3000 PSI)	.002 [m^3]
	Operating Pressure	.827 [MPa]
	Thrust per Thruster	.28 [N]
Attitude Control	MSGCMG Max Torque	.668 [Nm]
	MSGCMG Max Ang. Momentum	.098 [Nms]
Electrical & Electronic	Battery Type	Lithium-Ion
	Storage Cap @ 28 [V]	12 [Ah]
	Computers	2 PC-104, Pentium III
Sensors	Fiber Optic Gyro Bias	±20°/hr
	LIDAR	SICK 360 °
	iGPS Sensor Accuracy	<.050 [mm]
	Accelerometers Bias	±8.5x10^{-3} [g]
Floatation	Propellant	Air
	Equiv Storage Cap @ 21 [MPA] (3000 PSI)	.002 [m^3]
	Operating Pressure	.35 [MPa]
	Linear Air Bearings Diameter	32 [mm]

2^{nd}-generation Spacecraft Simulator [ctnd]

Mini Control Moment Gyroscopes



One of the two rotating thrusters



2[nd]-generation simulator: attitude dynamics

- Equation of motion for a rigid spacecraft with a CMG

$$\dot{\mathbf{H}}_s + \boldsymbol{\omega} \times \mathbf{H}_s = \mathbf{T}_{ext}$$

- H vector takes into account both main vehicle and CMG angular momentum

$$\mathbf{H}_s = \mathbf{J}\boldsymbol{\omega} + \mathbf{h}$$

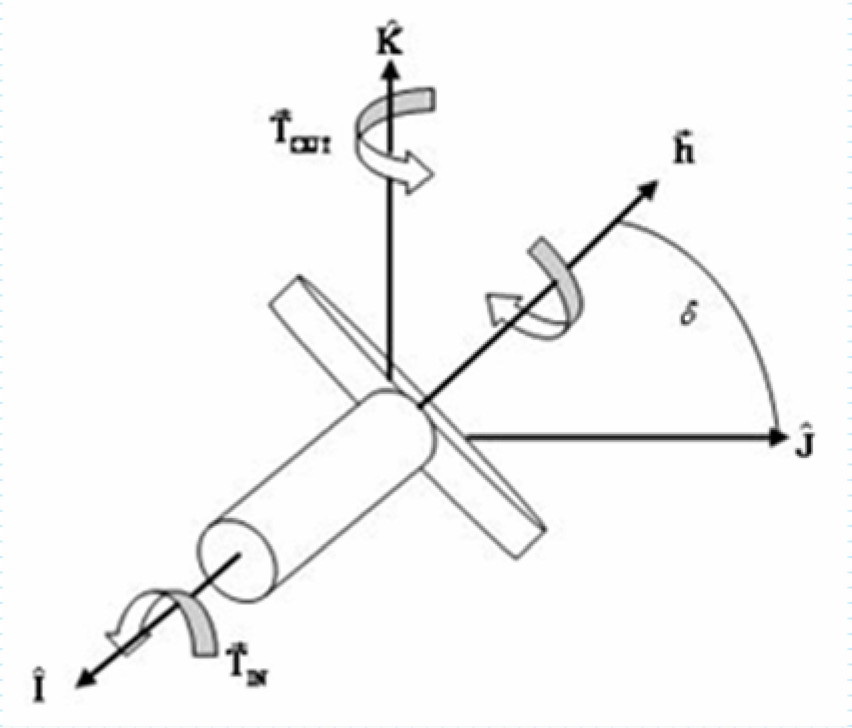
$$\mathbf{h} = h_w \left[0, \cos\delta, \sin\delta\right]^T$$

- The torque from the CMG is

$$\mathbf{J}_Z \dot{\boldsymbol{\omega}}_Z = \mathbf{T}_{CMG_Z} = -\dot{\mathbf{h}}_Z = \mathbf{u}_Z$$

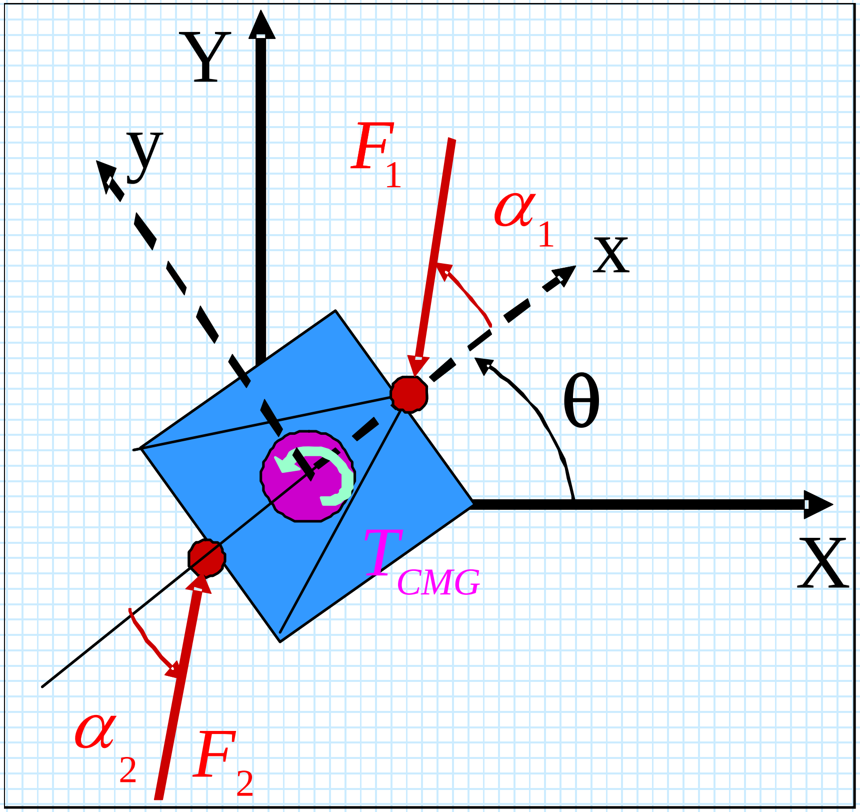
- The CMGs' steering law is

$$\dot{\mathbf{h}}_Z = h_W \cos\delta\dot{\delta} = -\mathbf{u}_Z$$

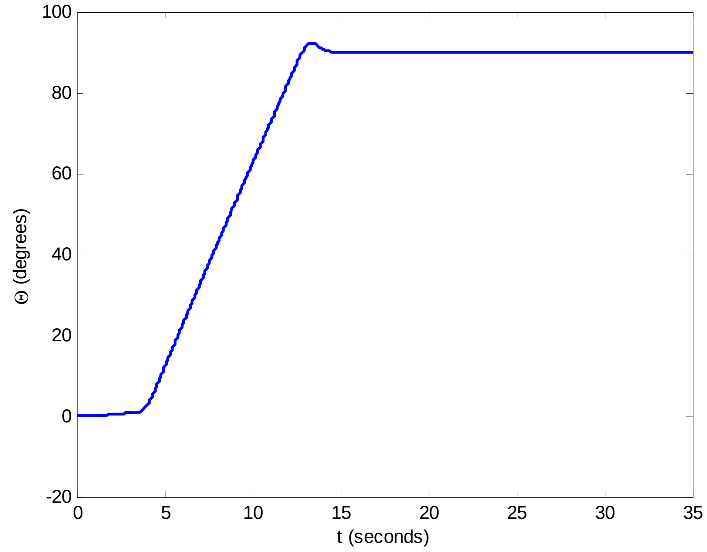


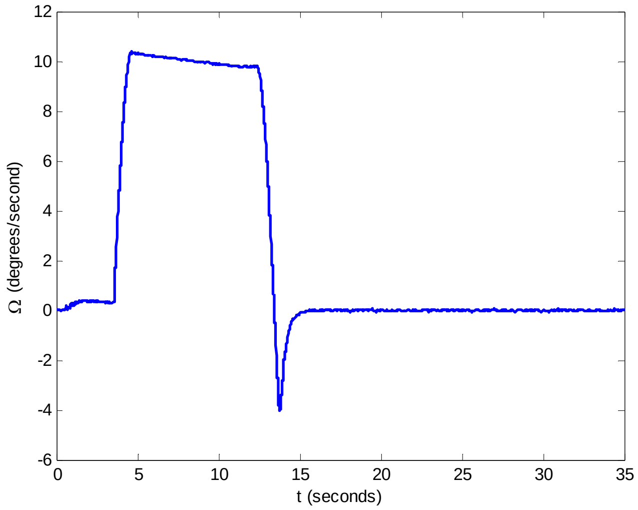
2^{nd}-generation simulator: rotational dynamics

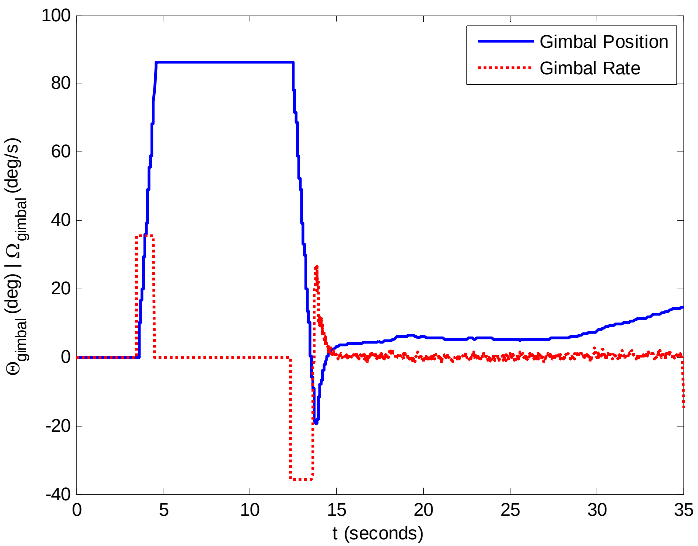
- State Variables
  - $x,\ y,\ \theta$
- Control Parameters
  - $F_1, F_2, \alpha_1, \alpha_2, T_{MSGCMG}$
- Dynamic Equations
  - $\ddot{X} = -F_1 \cos(\alpha_1 + \theta) + F_2 \cos(\alpha_2 + \theta)$
  - $\ddot{Y} = -F_1 \sin(\alpha_1 + \theta) + F_2 \sin(\alpha_2 + \theta)$
  - $\ddot{\theta} = T_{CMG} - F_1 d_1 \sin(\alpha_1) - F_2 d_2 \sin(\alpha_2)$

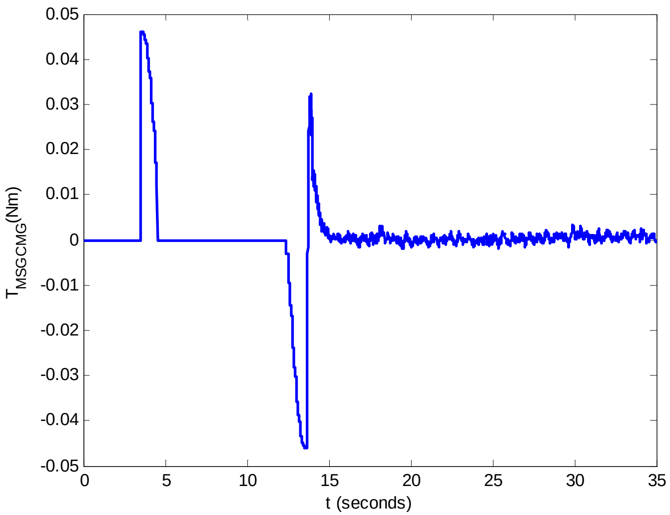


2^{nd}-generation simulator: Preliminary experiment









Conclusions

- A ProxOps Simulation facility and two kinds of Robotic Spacecraft Simulators have been developed
- Experiments of autonomous tracking and docking maneuvers were performed
- The research has a critical educational value
- Future development: multi-spacecraft assembly & reconfiguration

- For more information:

M.Romano, D.A. Friedman, T.J. Shay, Laboratory Experimentation of Autonomous Spacecraft Approach and Docking to a Collaborative Target. Accepted for publication. To Appear. AIAA Journal of Spacecraft and Rockets.

J. Hall, M. Romano, A Novel Robotic Spacecraft Simulator with Mini-Control Moment Gyroscopes and Rotating Thrusters. Submitted toe IEEE AIM 2007.

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