Autonomous Proximity Operations of Small Satellites with Minimum Numbers of Actuators

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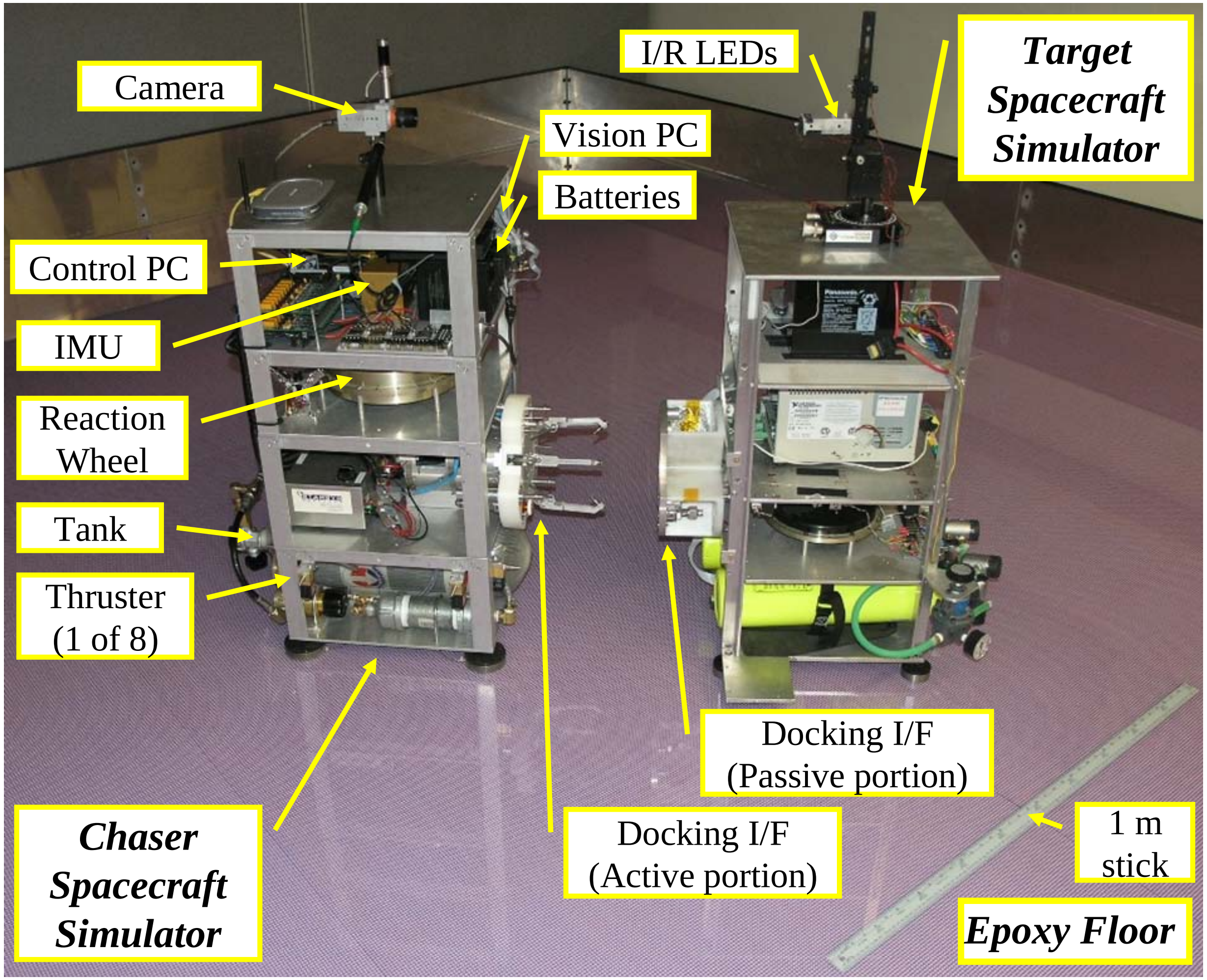
Spacecraft Robotics
LABORATORY

Outline

- Historical work in the Spacecraft Robotics Lab
- Benefits of 3DOF work WRT Proximity Operations
- Motivation for Rotating Thruster Configuration
- Equations of Motion Development
- Controllability of the Spacecraft Simulator
- Input-Output linearization Plus LQR
- Numerical simulation Results
- Conclusion

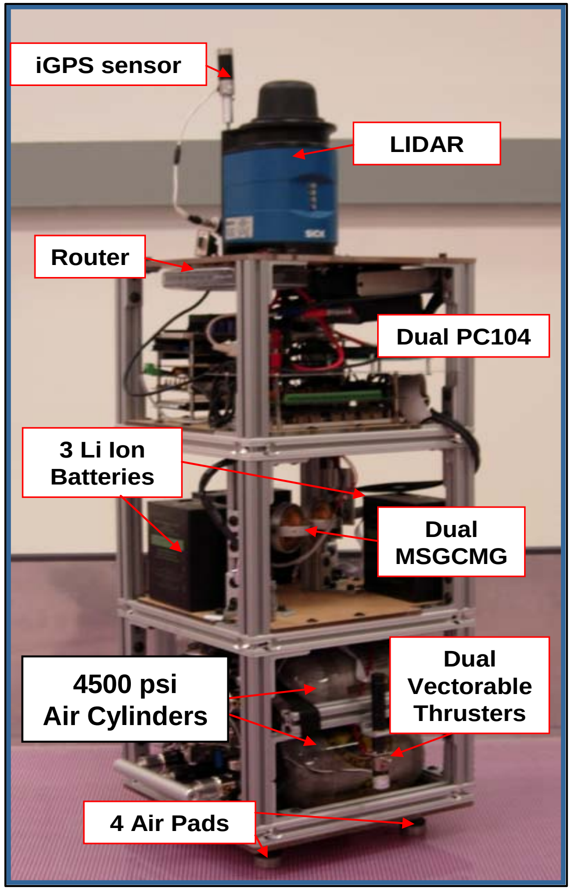
2005-2006: AUDASS: S/C Simulators on Flat Floor

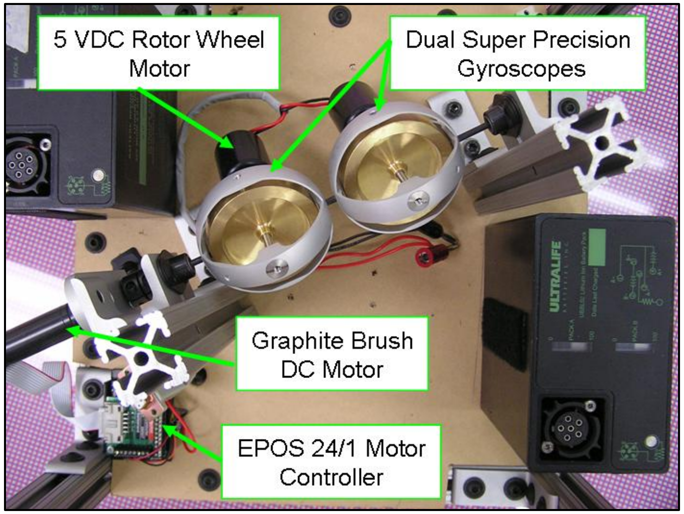


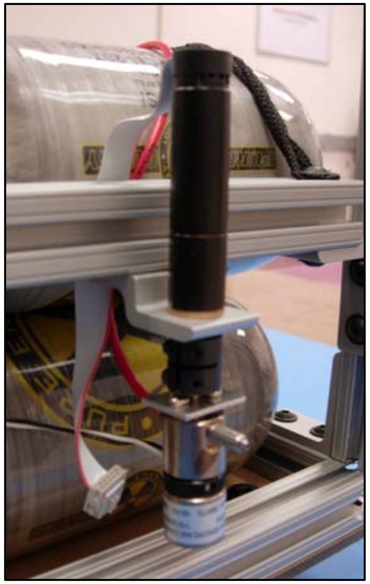
M. Romano, D.A. Friedman, T.J. Shay, *Laboratory Experimentation of Autonomous Spacecraft Approach and Docking to a Collaborative Target*, AIAA Journal of Spacecraft and Rockets, Vol. 44, No. 1, pp. 164-173, January-February 2007.

2006-Present: Interacting S/C w/ Micro-CMG & Rotating Thrusters

Autonomous Multi-Agent Physically Interacting Spacecraft (AMPHIS)



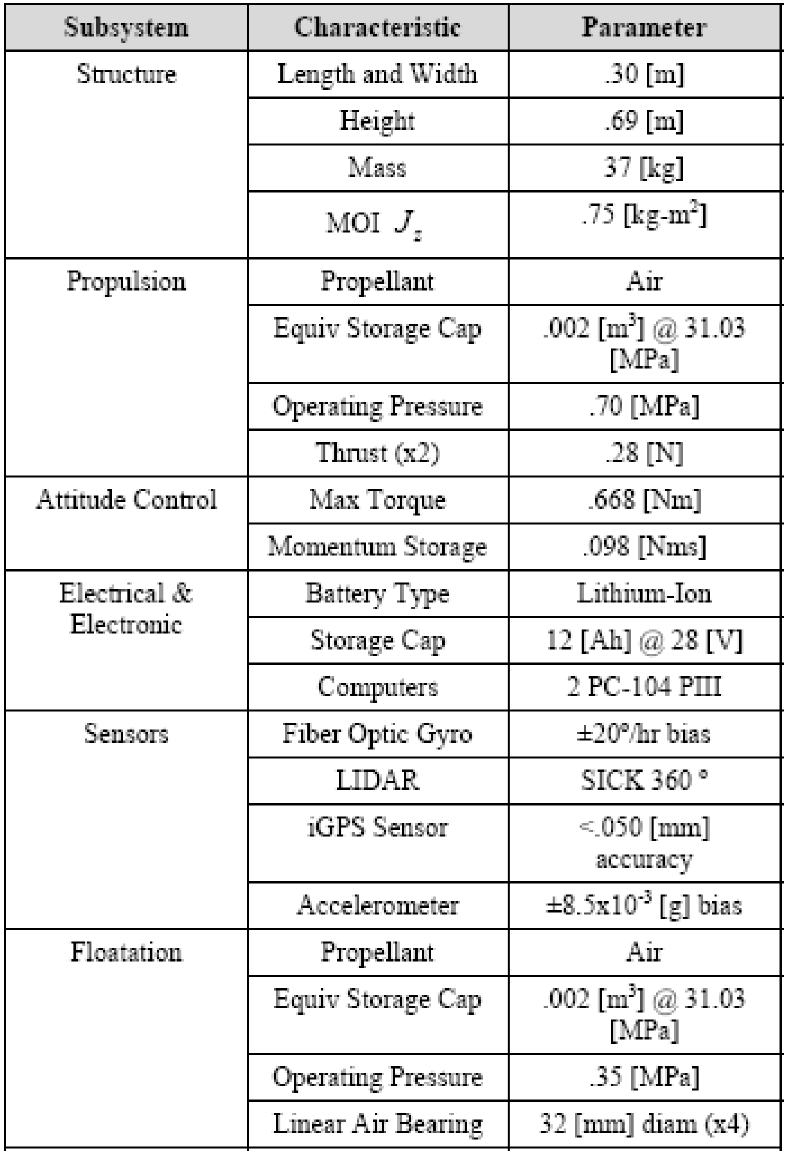




J. Hall, M. Romano, A Novel Robotic Spacecraft Simulator with Mini-Control Moment Gyroscopes and Rotating Thrusters. Submitted to IEEE AIM 2007.

Key AMPHIS Parameters

- Dual semi-circular rotating thrusters
    - Air propellant
    - .28 N max thrust
- Single-gimbaled miniature control moment gyro
    - .668 Nm max torque
    - .098 Nms momentum storage



Subsystem	Characteristic	Parameter
Structure	Length and Width	.30 [m]
	Height	.69 [m]
	Mass	37 [kg]
	MOI J_z	.75 [kg-m^2]
Propulsion	Propellant	Air
	Equiv Storage Cap	.002 [m^3] @ 31.03 [MPa]
	Operating Pressure	.70 [MPa]
	Thrust (x2)	.28 [N]
Attitude Control	Max Torque	.668 [Nm]
	Momentum Storage	.098 [Nms]
Electrical & Electronic	Battery Type	Lithium-Ion
	Storage Cap	12 [Ah] @ 28 [V]
	Computers	2 PC-104 PIII
Sensors	Fiber Optic Gyro	±20°/hr bias
	LIDAR	SICK 360 °
	iGPS Sensor	<.050 [mm] accuracy
	Accelerometer	±8.5x10^{-3} [g] bias
Floatation	Propellant	Air
	Equiv Storage Cap	.002 [m^3] @ 31.03 [MPa]
	Operating Pressure	.35 [MPa]
	Linear Air Bearing	32 [mm] diam (x4)

Benefits of 3DOF work on a flat floor

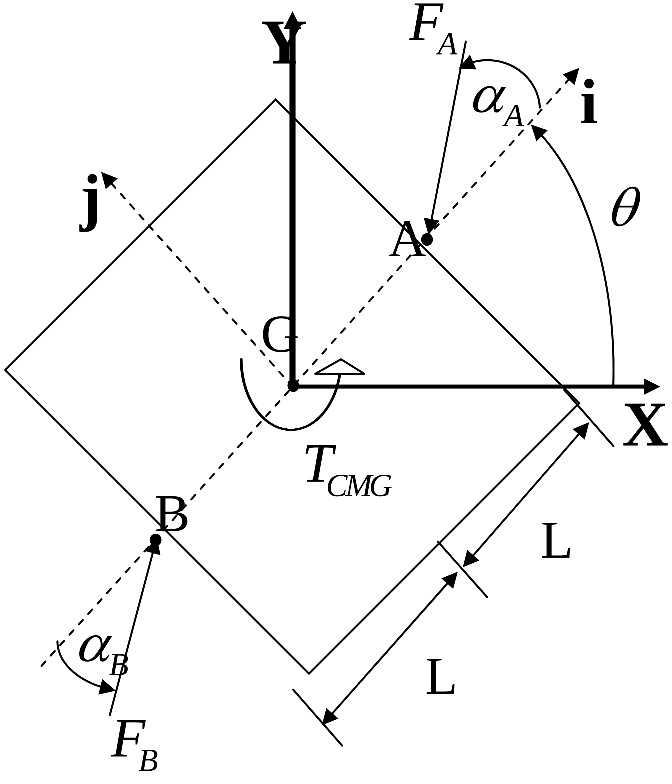
- With respect to spacecraft involved in proximity operations, the in-plane and cross-track dynamics are decoupled, as modeled by the Hill-Clohessy-Wiltshire (HCW) equations.
- With the orbital dynamics considered to be a disturbance during the proximity navigation phase of a rendezvous maneuver, the spacecraft navigation and control system can provide necessary compensation
- The hardware-in-the-loop nature of the flat floor test-bed can be used to fully reproduce the interaction of the GNC algorithms with the actual dynamics of the sensors, actuators and data transmission

Motivation for Rotating Thruster Configuration

- Advantages of vectorable thrusters
  - Ability to decrease propellant use through optimized thrust vectors
  - Free up both surface area and spacecraft volume for other components such as docking interfaces, sensor packages, payloads
  - Reduction in propulsion system complexity through the elimination of requisite valves and piping
- Disadvantages
  - Single String Control if one eliminates momentum exchange devices

AMPHIS Equations of Motion

- Developed using Lagrangian formulation
  - Generalized coordinates taken to be inertial position of the body (X,Y) and the angle of the body x-axis wrt to the inertial X-axis (θ)
- Kinetic Energy only due to the negligible slope of the flat floor and frictionless environment



AMPHIS Equations of Motion

- Well-studied control-affine system form where

$$\dot{\mathbf{X}} = \begin{bmatrix} \dot{X} \\ 0 \\ \dot{Y} \\ 0 \\ \dot{\theta} \\ 0 \\ \dot{\alpha}_A \\ 0 \\ \dot{\alpha}_B \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ \frac{-c\left(\theta+\alpha_A\right)}{m} & \frac{c\left(\theta+\alpha_B\right)}{m} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \frac{-s\left(\theta+\alpha_A\right)}{m} & \frac{s\left(\theta+\alpha_B\right)}{m} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \frac{-s\left(\alpha_A\right)}{J_z} & \frac{-s\left(\alpha_B\right)}{J_z} & \frac{1}{J_z} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{J_A} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{J_B} \end{bmatrix} \begin{bmatrix} F_A \\ F_B \\ T_{CMG} \\ T_A \\ T_B \end{bmatrix}$$

AMPHIS Equations of Motion with Proper Controls

- Resolving the thrust vectors from each thruster into their respective x and y components and providing a logic so that if the required force is negative use thruster A and positive use thruster B, the EOM are proper with respect to the controls

$$\ddot{X} = \frac{\cos\theta}{m} F_x - \frac{\sin\theta}{m} F_y$$

$$\ddot{Y} = \frac{\sin\theta}{m} F_x + \frac{\cos\theta}{m} F_y$$

$$\ddot{\theta} = \frac{-L}{J_z} F_y + \frac{1}{J_z} T_{CMG}$$

$$\ddot{\alpha}_{A,B} = \frac{1}{J_{A,B}} T_{A,B}$$

Notions of Controllability

- Small Time Local Controllability (STLC)
  - The reachable set is time limited in that it represents the set of all states that are reachable in a given time less than or equal to a desired time.
    - I can get where I want when I want
  - Most naturally suited for environments with obstacles or path constraints.
  - If the initial state is taken to be zero for control-affine systems with drift, then STLC can be studied in this vicinity
  - Can be determined using Lie Algebra methods

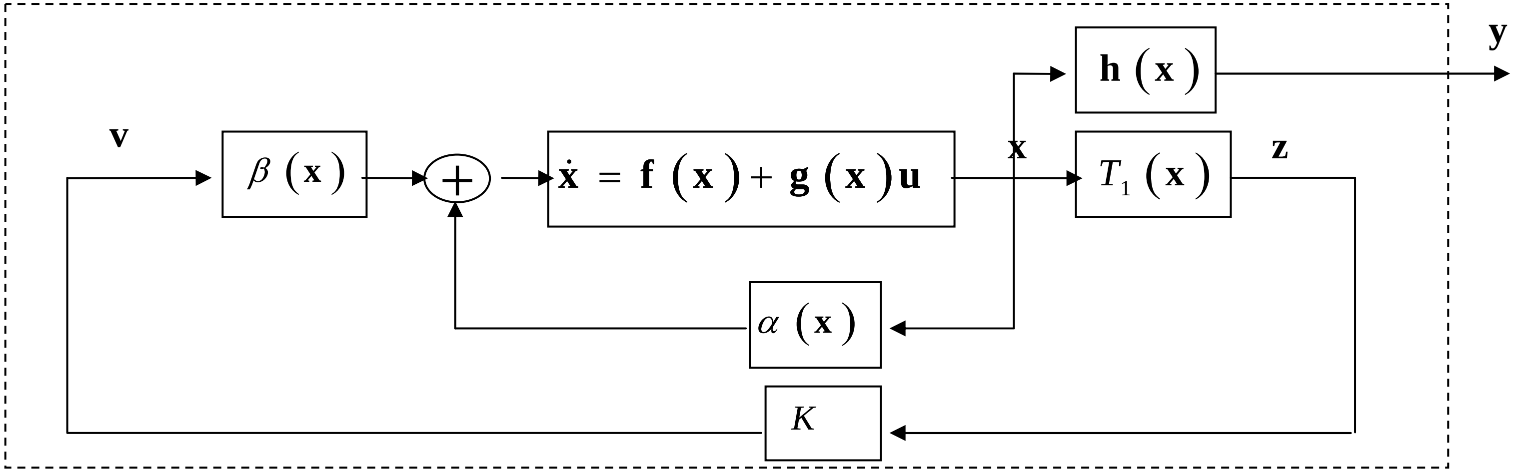
Summarization of STLC Results for AMPHIS simulator

- Considering different combinations of actuators for the 3-DoF AMPHIS simulator, a complete development of the controllability of the system can be found
- The system is STLC with only the paired vectorable thruster configuration (as highlighted)

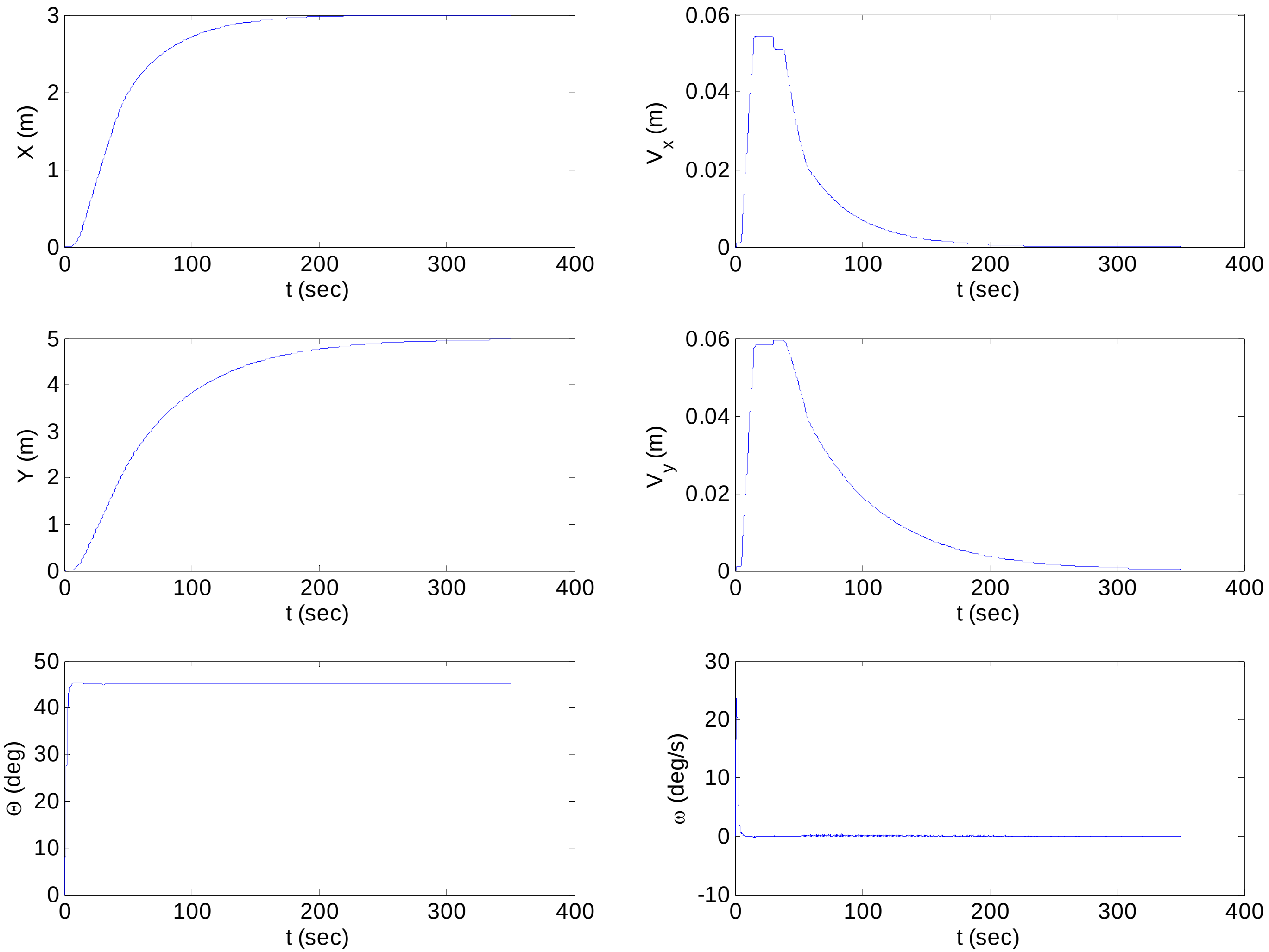
Actuators	**Lie Algebra Rank Condition**	**STLC**
F_X only	8	No
F_y only	9	No
F_X and F_y	10	Yes
F_X and T_{CMG}	10	Yes
F_y and T_{CMG}	9	No

Input-Output Linearization

- A decoupling nonlinear control law can be found to feedback linearize this nonlinear system where there are no internal dynamics
- The linearized system can then be feedback stabilized using standard linear control system theory. For initial studies, a Linear Quadratic Regulator is employed, yielding satisfactory results.



Simulation Results $\mathbf{x}_0 = \mathbf{0}, x_f = 3, y_f = 5, \theta_f = 45 \text{ deg}$



Simulation Results

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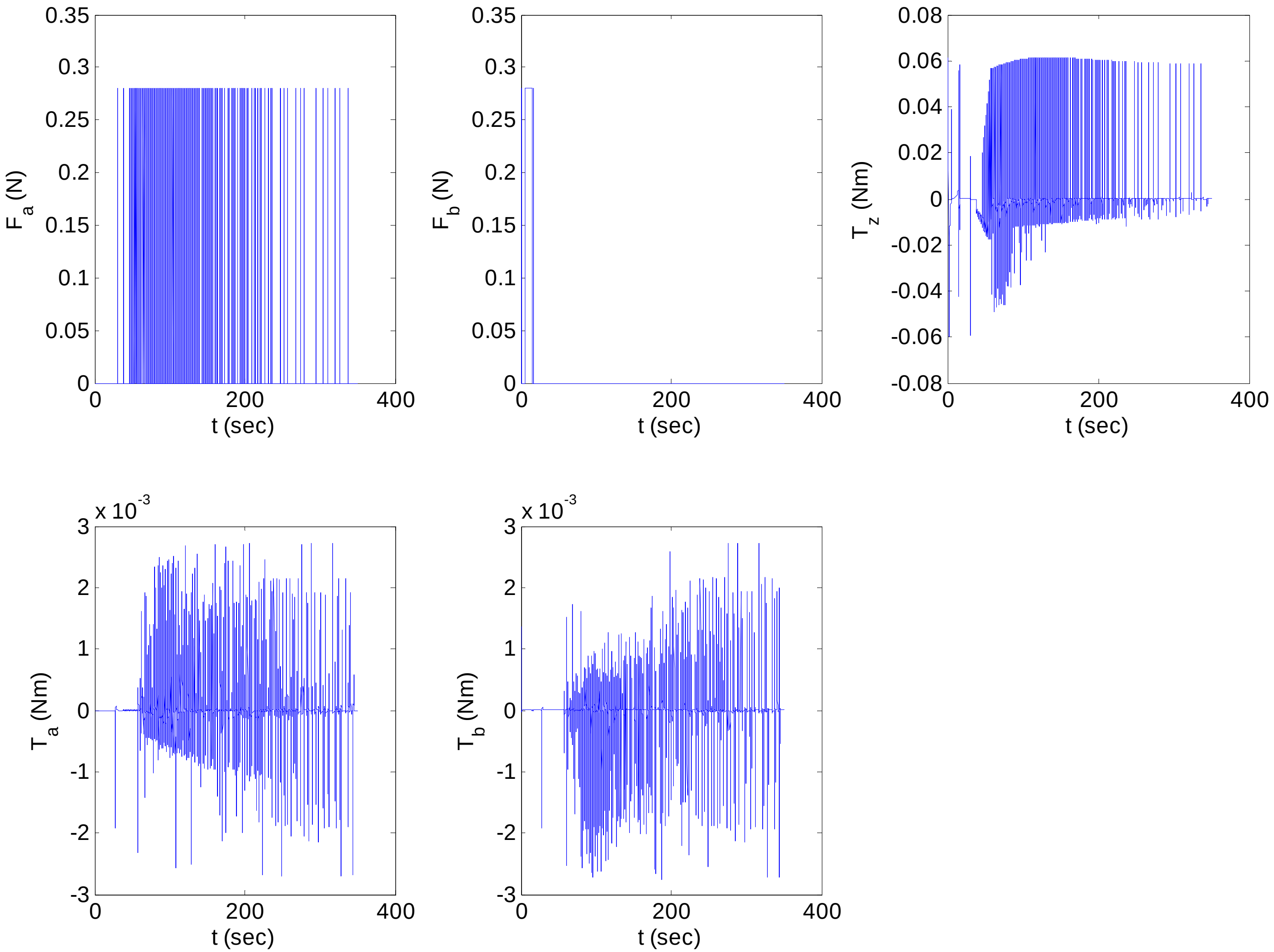

Conclusion

- Application of rotating thrusters to full 6-DOF spacecraft model
  - Need to consider drift vector (non-zero initial condition for standard keplarian model)
  - Consider HCW equations where equilibrium point is center of RSW coordinate system and can achieve zero initial condition
  - Preliminary results using Lie algebra methods show that two hemi-spherical opposite face mounted thrusters can provide STLC (Canfield Joint)
- Tests on AMPHIS testbed verified simulation results

Acknowledgement

- We would like to thank
  - Previous Master's students LCDR Blake Eikenberry and LT Bill Price
  - Our research sponsor DARPA

Movies

Hemispherical Joint Firing Demonstration

Courtesy: Dr. Stephen Canfield, Professor,
Mechanical Engineering, Tennessee Tech University

AMPHIS Demonstration

Simulation Video