COE CST First Annual Technical Meeting: Task 244: Autonomous Rendezvous & Docking for Space Debris Mitigation

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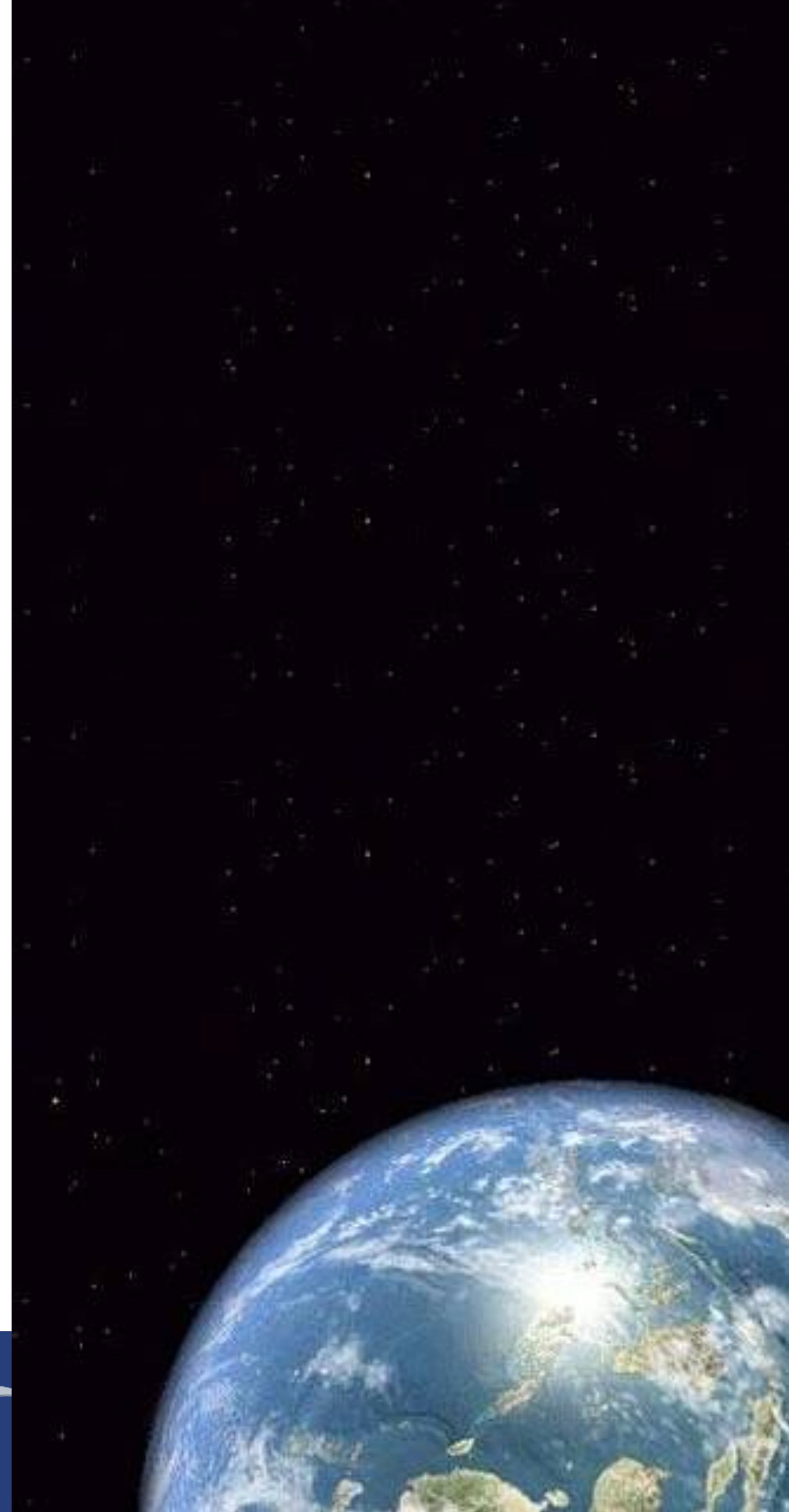


Overview

- Team Members
- Purpose of Task
- Research Methodology
- Results
- Next Steps
- Contact Information

Team Members

- Norman G. Fitz-Coy (PI, University of Florida)
- Takashi Hiramatsu (University of Florida)

Purpose of Task - Motivation

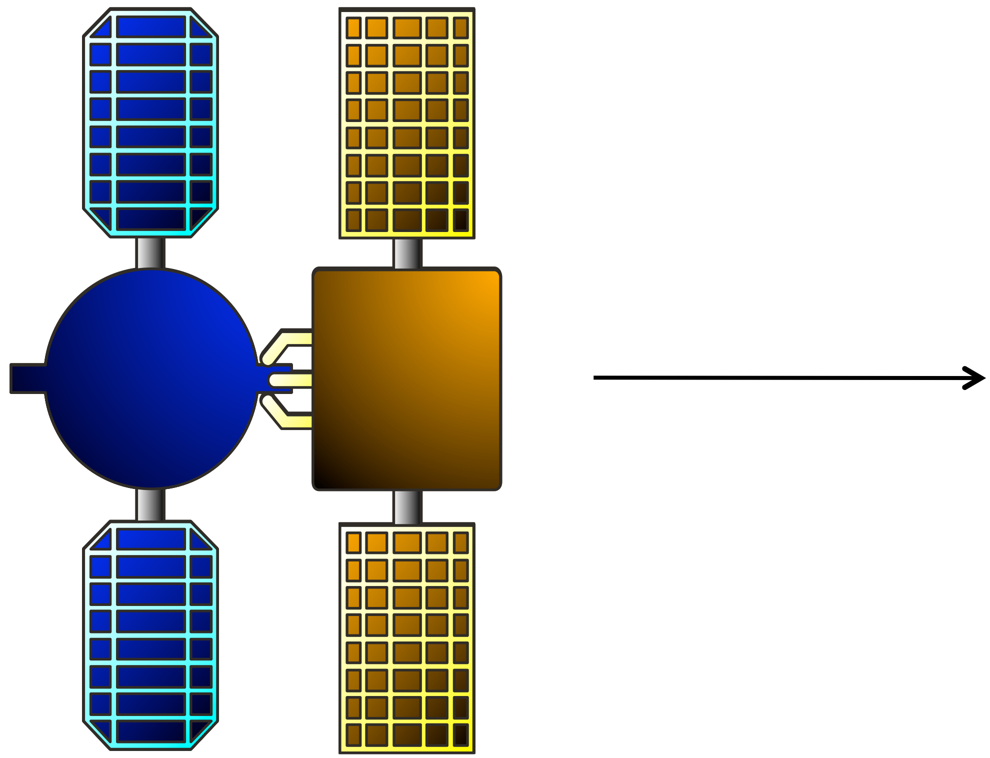
- Remediation requires active space debris removal
- Proliferation of CubeSat form factor satellites leads to
  - More spacecraft = more failure
  - 52 CubeSats launched since 2003, 23 active (~44% success)
  - Disabled spacecraft = debris
- Malfunction in actuator, communication, etc.
  - Non-cooperative behavior pre/post docking

Purpose of Task

- Objective
  - Minimize interaction “forces” between vehicles when docked with a non-cooperative target
- Goals
  - Characterize the non-cooperative post-docking with “disabled spacecraft” (i.e., debris)
  - Develop necessary control strategy to counteract debris’s motion and maintain a safe docked state

Towing Debris

- React to disturbances through rotational motion
  - None (cooperative)
  - Translational
  - Rotational



Debris
(leader)

Service vehicle
(follower)

Methodology: Game Theory

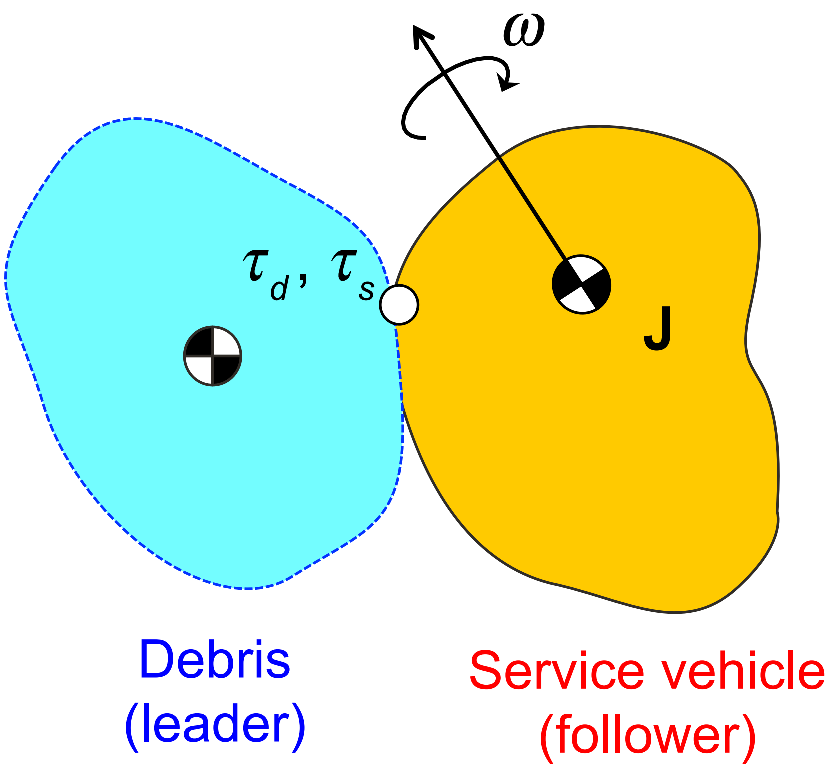
- Game Theoretic Approach
  - Multiple players (debris, service vehicle)
  - Make an intelligent estimate of the debris's behavior to compute the reacting control strategy of the service vehicle
- Stackelberg Game
  - System with leader-follower hierarchy
  - Interaction with a non-cooperative spacecraft (leader)

Methodology: Rotational Dynamics

- SV's rotational motion

$$\mathbf{J}\dot{\omega} + \omega^{\times}\mathbf{J}\omega = \tau + \tau_d + \tau_s$$

  - τ : control torque input
  - τ_d : interaction due to non-cooperative behavior
  - τ_s : interaction due to orientation mismatch
- Design τ to minimize the interaction



Methodology: Controller Design

- Rewrite to get Euler-Lagrange system

$$\mathbf{J}\dot{\omega} + \omega^{\times}\mathbf{J}\omega = \tau + \tau_d + \tau_s \longrightarrow \mathbf{M}\ddot{\mathbf{q}} + \mathbf{V}_m\dot{\mathbf{q}} + \mathbf{g} = \tau_d + \tau$$

- Define errors $\mathbf{e}_1 = \mathbf{q}_d - \mathbf{q}$ $\quad \mathbf{e}_2 = \dot{\mathbf{e}}_1 + \alpha_1\mathbf{e}_1$
- Derive Error dynamics

$$\mathbf{M}\dot{\mathbf{e}}_2 = -\mathbf{V}_m\mathbf{e}_2 - \tau + \mathbf{h} + \tau_d$$

- Break τ into two controllers $\tau = \mathbf{h} - \mathbf{u}$
- Formulate linear error model

$$\dot{\mathbf{e}}_1 = -\alpha_1\mathbf{e}_1 + \mathbf{e}_2$$

$$\dot{\mathbf{e}}_2 = -\mathbf{M}^{-1}\mathbf{V}_m\mathbf{e}_2 - \mathbf{M}^{-1}\mathbf{u} + \mathbf{M}^{-1}\tau_d$$

Methodology: Differential Game

- 2-player linear quadratic differential game

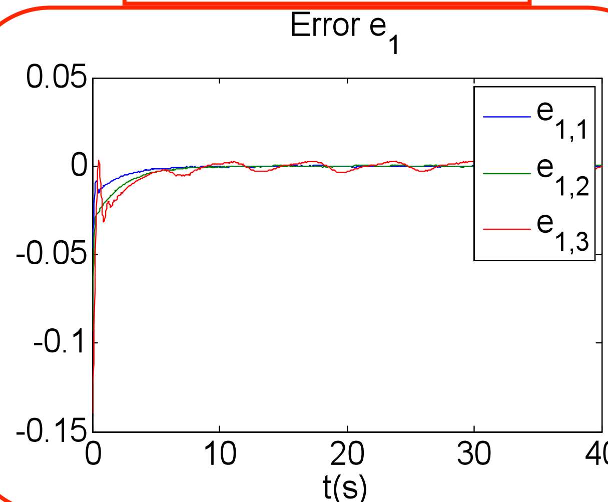
$$J_1 = \frac{1}{2}\int_0^\infty \left(\mathbf{x}^T\mathbf{Q}\mathbf{x} + \mathbf{u}^T\mathbf{R}_{11}\mathbf{u} + \tau_d^T\mathbf{R}_{12}\tau_d\right)dt$$

$$J_2 = \frac{1}{2}\int_0^\infty \left(\mathbf{x}^T\mathbf{N}\mathbf{x} + \mathbf{u}^T\mathbf{R}_{21}\mathbf{u} + \tau_d^T\mathbf{R}_{22}\tau_d\right)dt$$

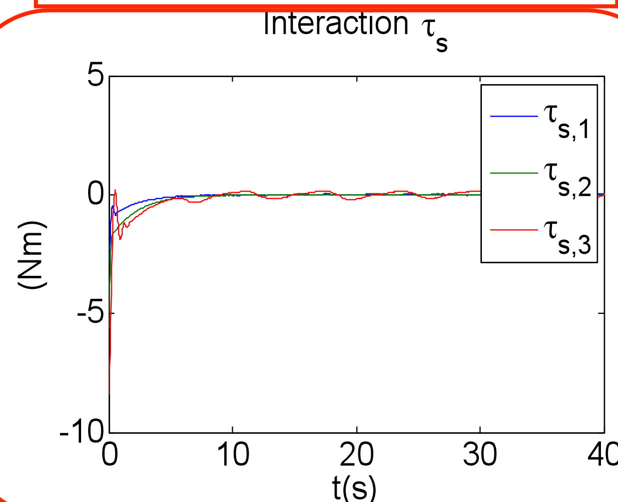
- s.t. $\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}_1\mathbf{u} + \mathbf{B}_2\tau_d \quad \mathbf{x} = \begin{bmatrix} \mathbf{e}_1^T & \mathbf{e}_2^T \end{bmatrix}^T$
- Solve using Stackelberg strategy
  - Leader-follower hierarchy
  - Debris as the leader

Results

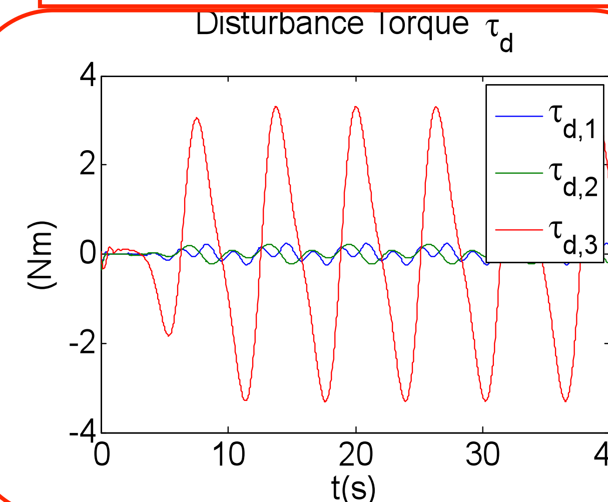
Attitude Error

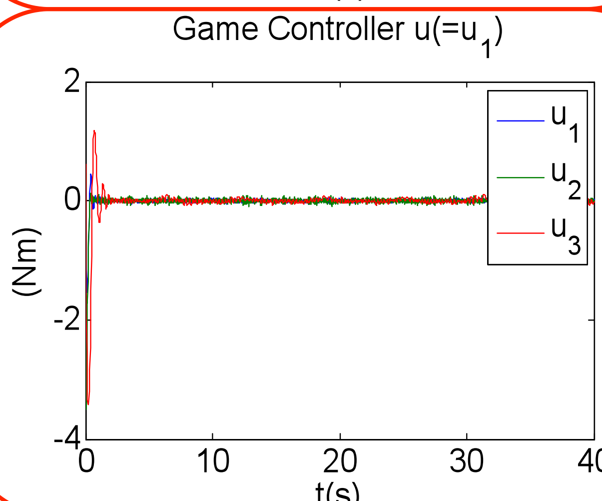


Interaction

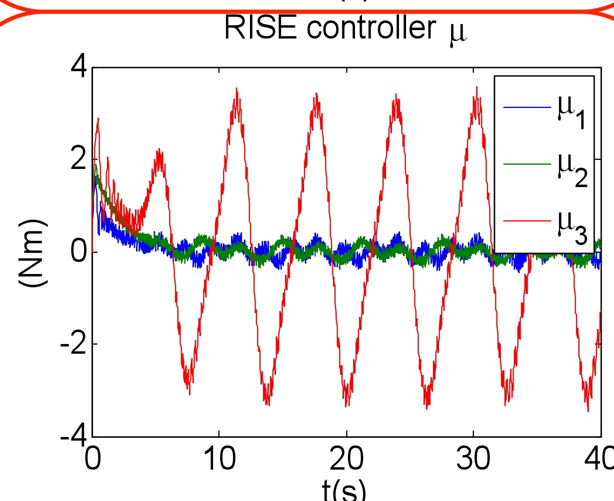


Debris's Torque

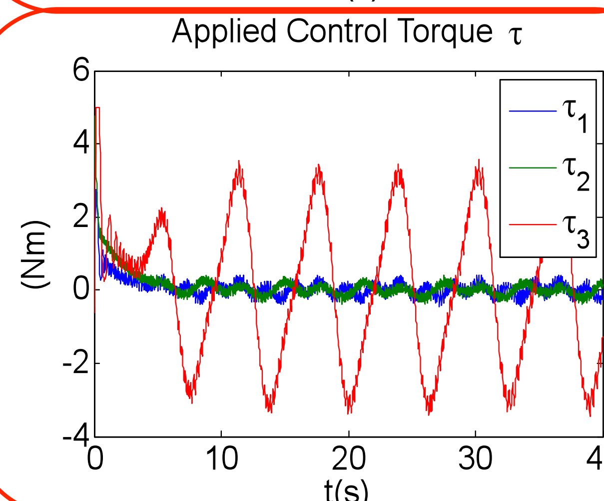




Game Controller



Feedback Linearizer



Total Control Torque

Summary

- Preliminary analysis shows promise for removal of non-cooperative debris
  - Game theory with Stackelberg strategy
    - addresses the post-dock interactions
    - lowers interactions between service vehicle and debris
- Developed solution preserves nonlinearity of system dynamics (linearity in the error model)

Next Steps:

- Add constraints to the control effort
- Extend the controller design to a multiplicative error model

	Year 1	Year 2	Year 3
Trajectory Planning	Assessment of the state of the art for active debris removal	Assessment of hardware implementation issues in APFG collision avoidance and SBMPC	Hardware assessment of all developed methodologies
Proximity operation		APFG collision avoidance strategies	Hardware implementation issues in APFG and SBMPC
Post-docking	**Initial assessment of post-dock scenarios**	Continued assessment of post-dock scenarios	Hardware assessment of all developed methodologies

Contact Information

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