ONLINE CONTROL AND MOMENT OF INERTIA ESTIMATION OF TETHERED DEBRIS

Liam Field, Derek Bourabah*, Eleonora M. Botta

University at Buffalo
Department of Mechanical and Aerospace Engineering
School of Engineering and Applied Sciences

2024 SciTech Forum
Orlando, January 8 – 12, 2024

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Outline

- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Outline

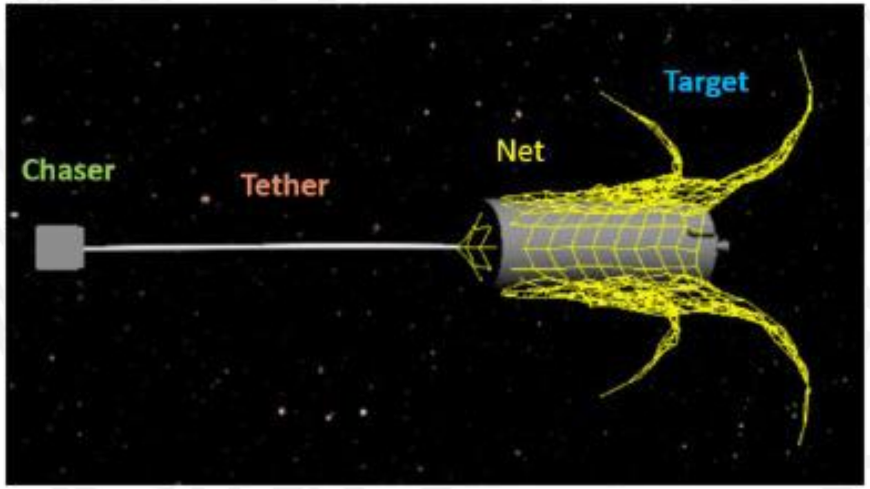
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Introduction

Tether-based Capture of Debris

- Tether-based capture of debris include tether nets and harpoons
  - Safer capture of debris (longer distances can be maintained)
  - More difficult to control
    - De-tumbling, model prediction, collision prevention, etc.
    - Chaotic motion, coupled dynamics
    - Unknown debris parameters and states



(Botta et al. 2020)

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Introduction

Prior work by our lab:

- Controls (Field and Botta [1])
  - Maintain safe operations
  - Assume known debris tether attachment point, attitude, and position
- Estimation (Bourabah et. al. [2])
  - Estimate attitude, angular rate, and principal Mass Moments of Inertia (MMI)
  - Assume controls know true debris states

This work performs estimation and control simultaneously

(i.e., controls don't assume known debris states)

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Outline

- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

System Model

- Rigid body chaser and debris connected by massless, extensible tether modeled as a single spring-damper

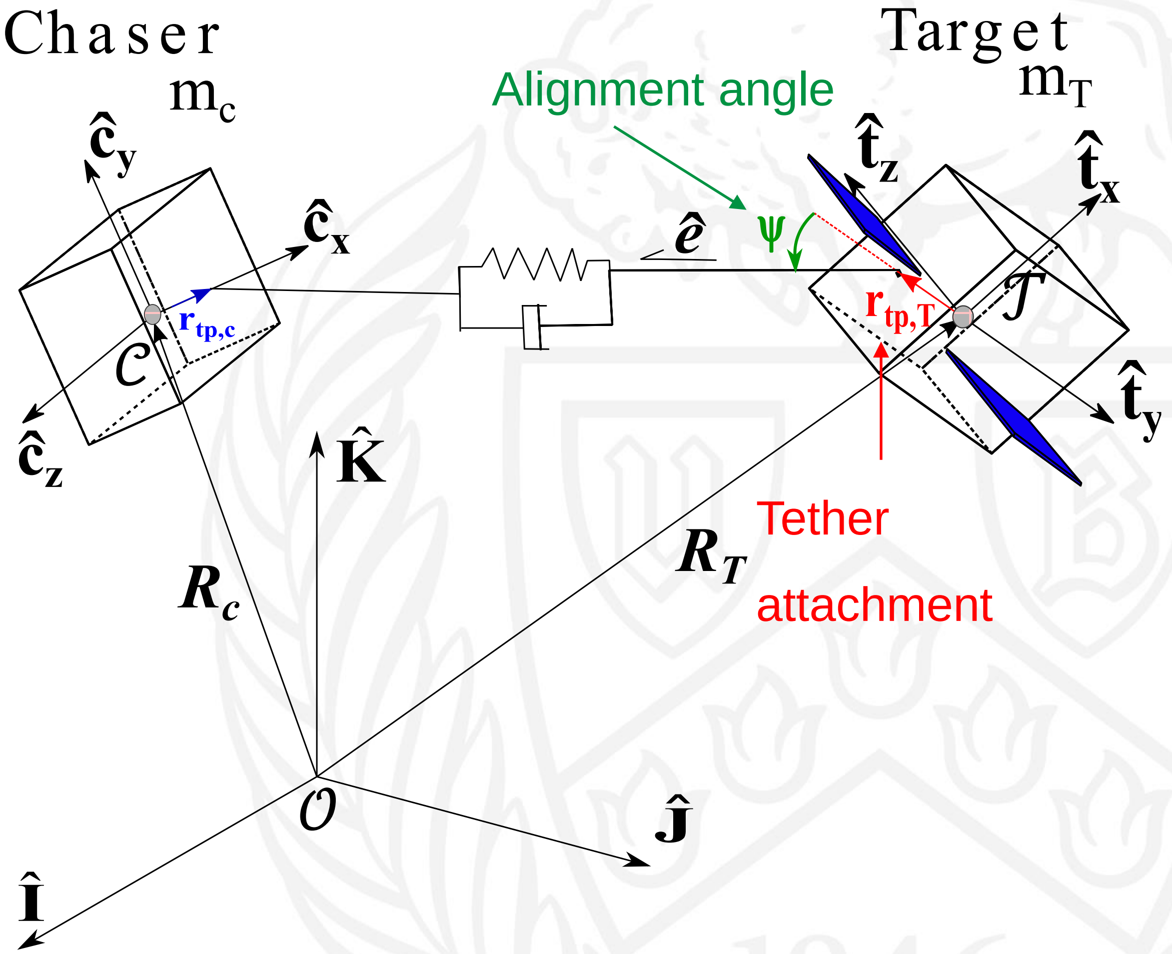
$\mathcal{O}[\hat{\boldsymbol{I}}, \hat{\boldsymbol{J}}, \hat{\boldsymbol{K}}]$: ECI frame

$\mathcal{C}[\hat{\boldsymbol{c}}_x, \hat{\boldsymbol{c}}_y, \hat{\boldsymbol{c}}_z]$: Chaser body frame

$\mathcal{T}[\hat{\boldsymbol{t}}_x, \hat{\boldsymbol{t}}_y, \hat{\boldsymbol{t}}_z]$: Target body frame

$\boldsymbol{r}_{tp}$: Tether attachment point

Ψ: Alignment angle



- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Challenges

Controls

- Require knowledge of debris states (Attitude, angular rates)

↓

Estimated

- Requires knowledge of chaser states

↓

Assumed known

Estimation

- Requires knowledge of acting moments on target

↓

Debris connected via tether

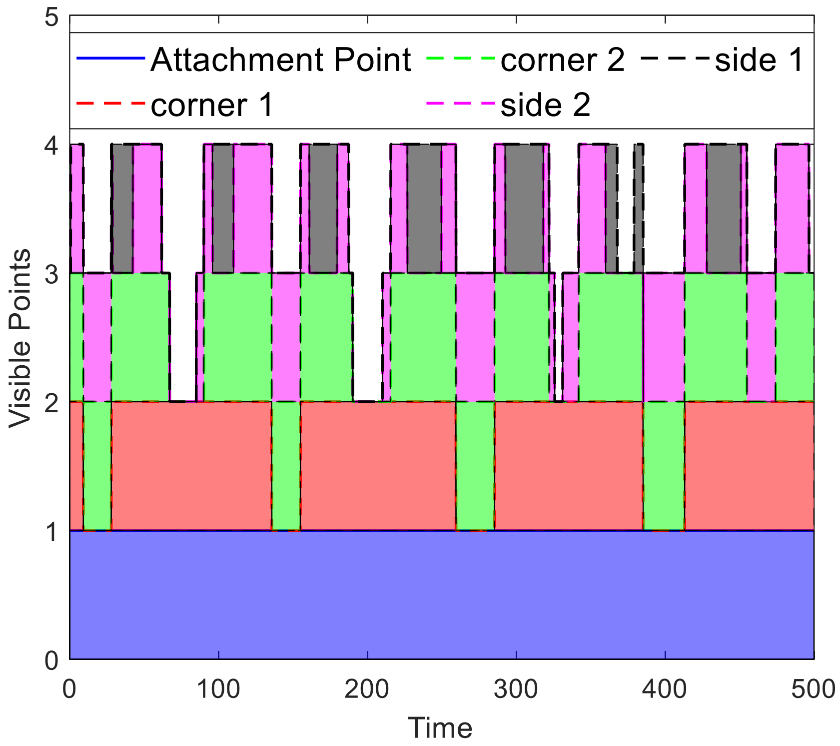
↓

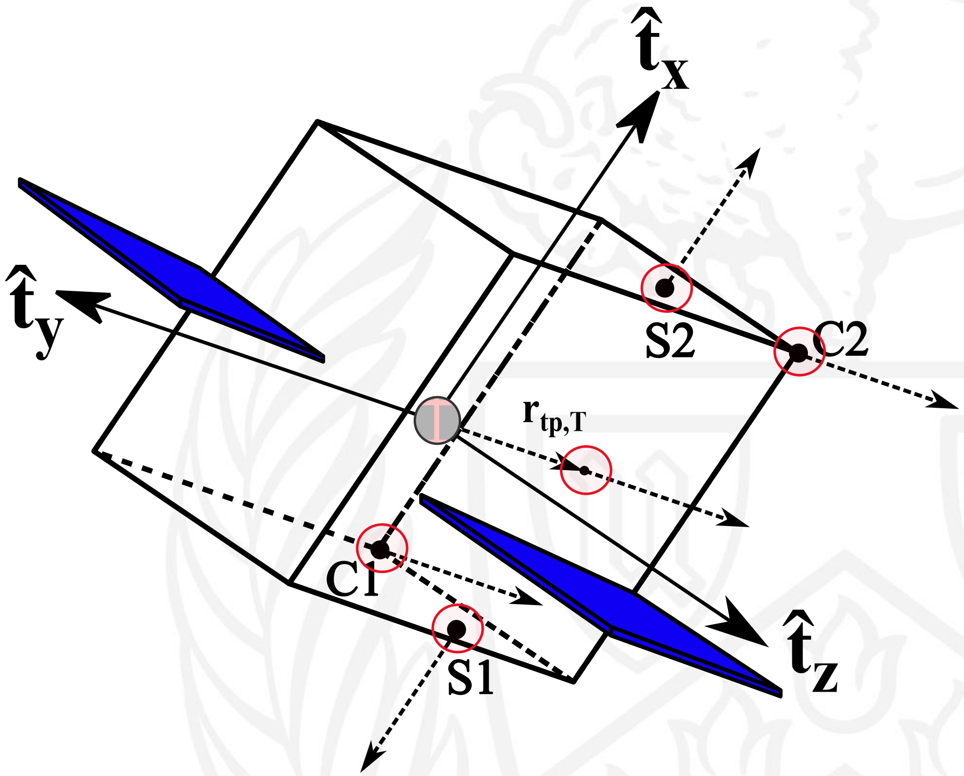
Tether tension provides moment for estimation

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Camera-Tracked Debris Features

- 5 tracked features
  - 3 on –y face of debris
  - 1 each on +/-x face of debris



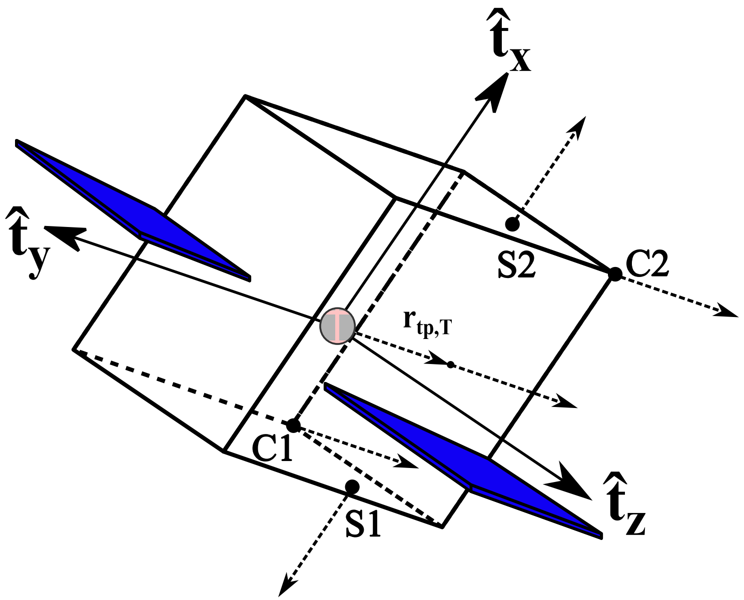


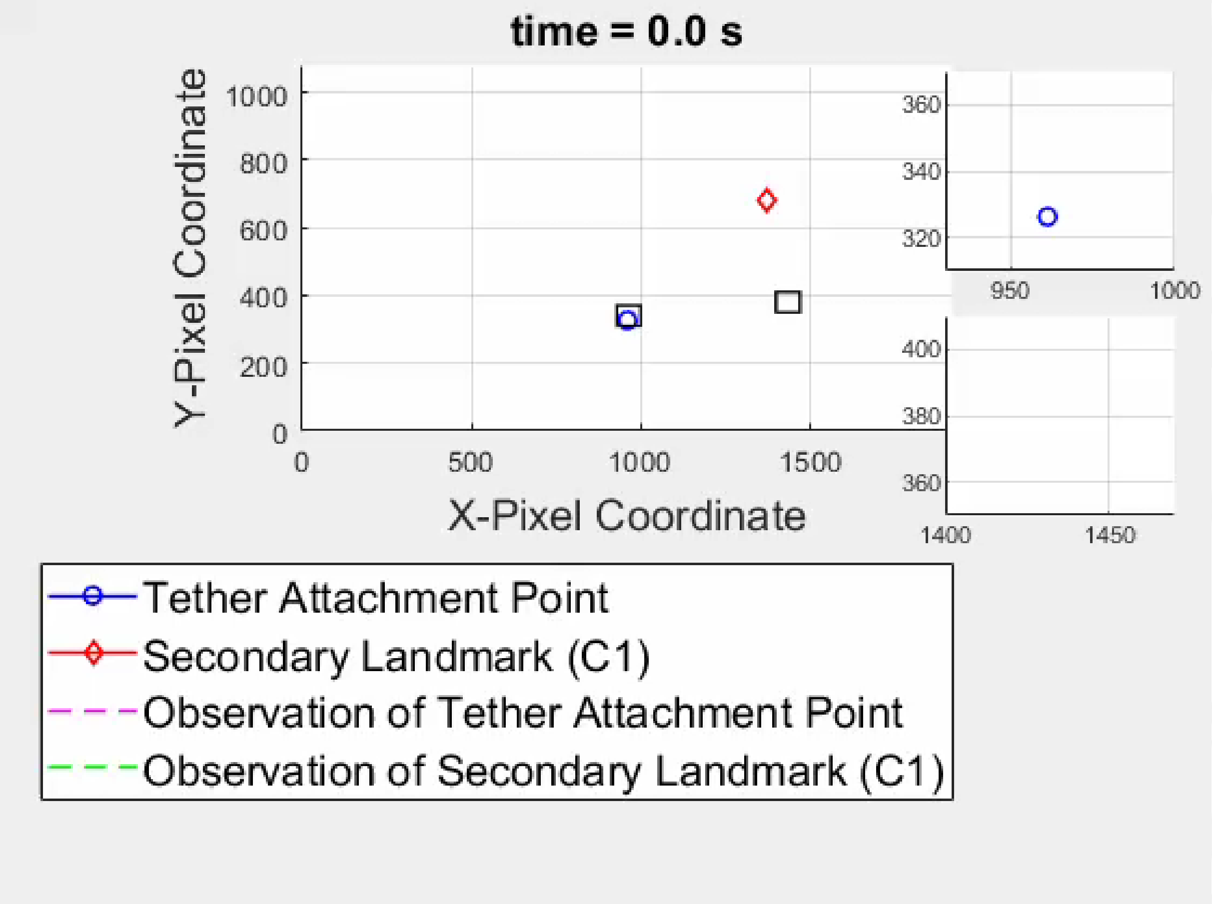
University at Buffalo
Department of Mechanical and Aerospace Engineering
School of Engineering and Applied Sciences

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Camera Model w/ Occlusion

- Assume known tether attachment points in respective body frames
- Camera generates pixel coordinate measurements of various debris features





- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Unscented Kalman Filter Dynamics

- Unscented Quaternion Estimator UKF, States:

$$\boldsymbol{X} = [\delta p_x, \delta p_y, \delta p_z, \omega_x, \omega_y, \omega_z, J_x, J_y, J_z]^T$$

- Measurement model utilizes tension and pixel coordinate measurements ($\boldsymbol{h}(\boldsymbol{x}) = [T, p_x, p_y]^T$)

- Measured tension used directly in dynamics

$$\begin{bmatrix} \dot{\hat{q}}_1 \\ \dot{\hat{q}}_2 \\ \dot{\hat{q}}_3 \\ \dot{\hat{q}}_4 \\ \dot{\hat{\omega}}_x \\ \dot{\hat{\omega}}_y \\ \dot{\hat{\omega}}_z \\ \dot{\hat{J}}_x \\ \dot{\hat{J}}_y \\ \dot{\hat{J}}_z \end{bmatrix} = \begin{bmatrix} (\hat{q}_4\hat{\omega}_x - \hat{q}_3\hat{\omega}_y + \hat{q}_2\hat{\omega}_z)/2 \\ (\hat{q}_3\hat{\omega}_x + \hat{q}_4\hat{\omega}_y - \hat{q}_1\hat{\omega}_z)/2 \\ (\hat{q}_1\hat{\omega}_y - \hat{q}_2\hat{\omega}_x + \hat{q}_4\hat{\omega}_z)/2 \\ (-\hat{q}_1\hat{\omega}_x - \hat{q}_2\hat{\omega}_y - \hat{q}_3\hat{\omega}_z)/2 \\ (r_y\hat{T}_z - r_z\hat{T}_y - \hat{\omega}_y\hat{J}_z\hat{\omega}_z + \hat{\omega}_z\hat{J}_y\hat{\omega}_y)/\hat{J}_x \\ (r_z\hat{T}_x - r_x\hat{T}_z - \hat{\omega}_z\hat{J}_x\hat{\omega}_x + \hat{\omega}_x\hat{J}_z\hat{\omega}_z)/\hat{J}_y \\ (r_x\hat{T}_y - r_y\hat{T}_x - \hat{\omega}_x\hat{J}_y\hat{\omega}_y + \hat{\omega}_y\hat{J}_x\hat{\omega}_x)/\hat{J}_z \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Relative Distance Control

- Proportional-Integrative-Derivative Controller
  - Reach and maintain a desired elongation, Δl
  - Process variable: $\hat{e}_k = \Delta l + l_0 - \hat{l}_k^-$

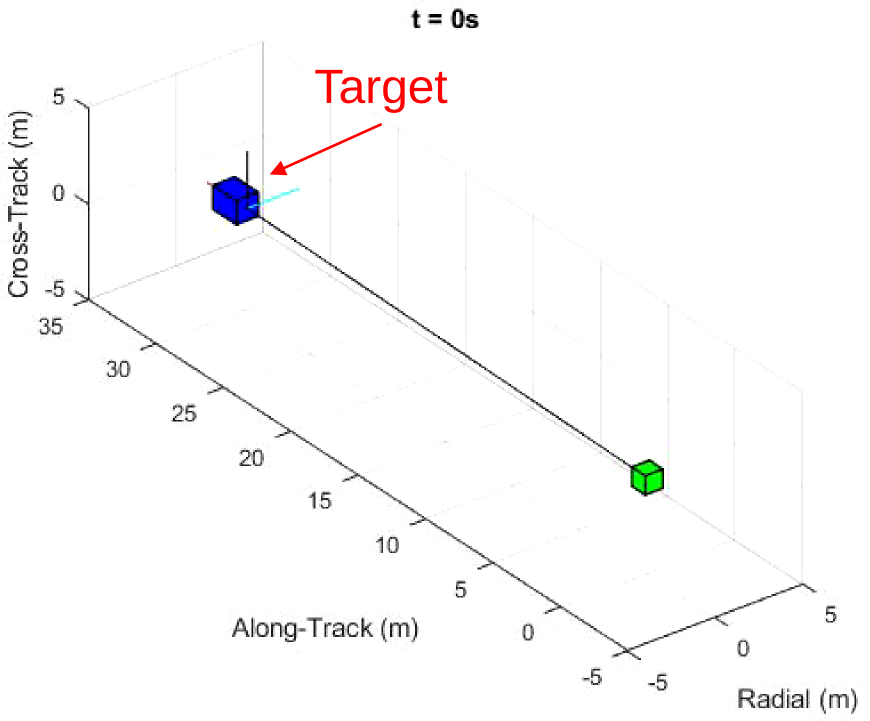
$$\hat{l}_k^- = ||\boldsymbol{R}_C + ^{\mathcal{O}} \boldsymbol{r}_{tp,C} - \boldsymbol{R}_T - ^{\mathcal{O}} \hat{\boldsymbol{r}}_{tp,T}||$$

  - Determines thrust:

$$\boldsymbol{U} = -\left(K_P \hat{e}_k + K_I \int_0^t \hat{e}_k dt + K_D \dot{\hat{e}}_k\right) \frac{\boldsymbol{V}_C}{||\boldsymbol{V}_C||}$$

    - Uses estimated debris states and parameters: $\dot{\hat{e}}_k = -\dot{\hat{l}}_k^-$

$$\dot{\hat{l}}_k^- = (\boldsymbol{V}_C + ^{\mathcal{O}} \boldsymbol{A}^{\mathcal{C}} \boldsymbol{\omega}_C \times ^{\mathcal{C}} \boldsymbol{r}_{tp,C} - \boldsymbol{V}_T - ^{\mathcal{O}} \hat{\boldsymbol{A}}^{\mathcal{T}} \hat{\boldsymbol{\omega}}_T \times ^{\mathcal{T}} \boldsymbol{r}_{tp,T}) \cdot \frac{\boldsymbol{V}_C}{||\boldsymbol{V}_C||}$$

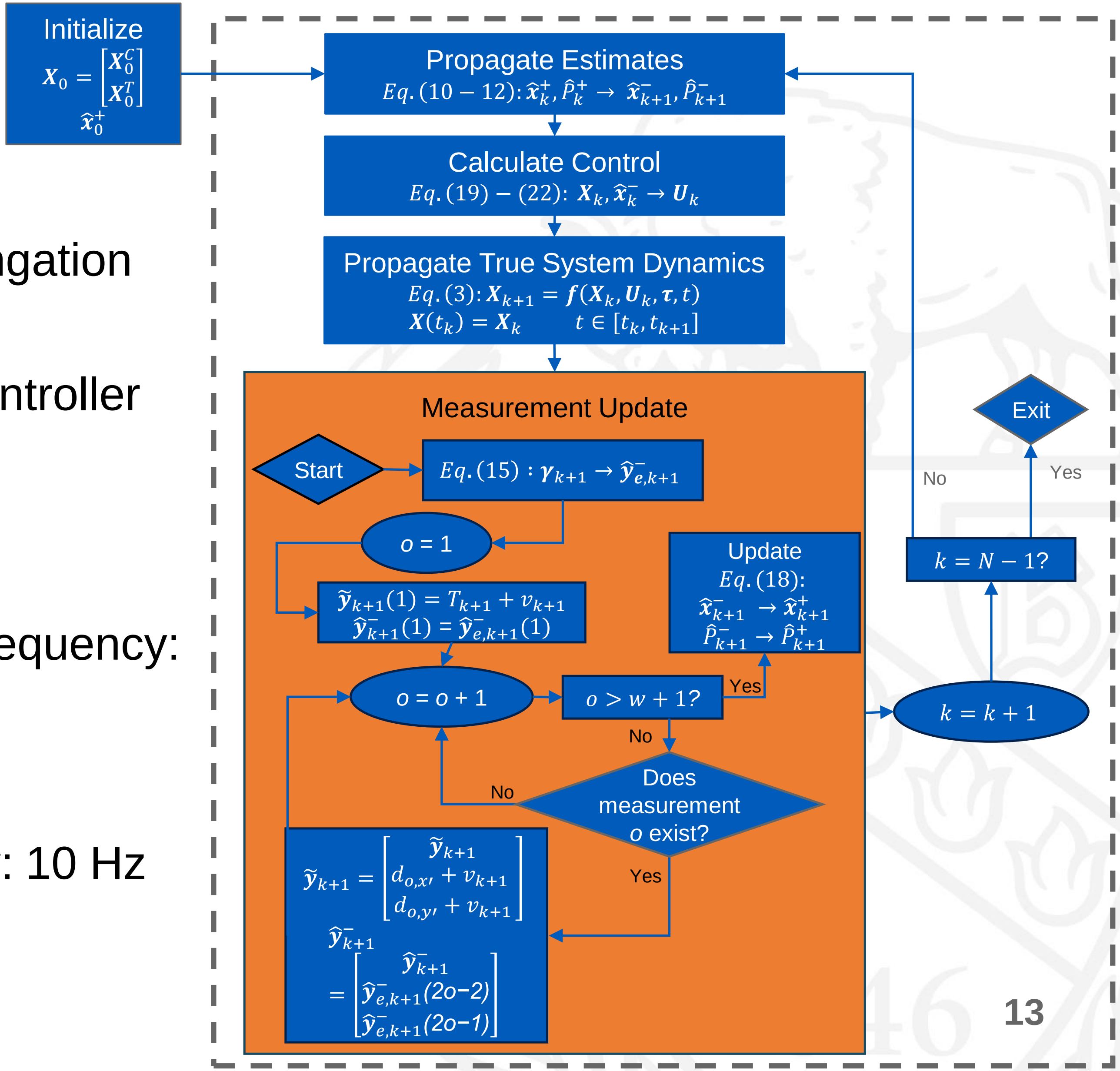


- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Control Diagram

- Control
  - Reach and maintain desired elongation
  - 50 N saturation
  - *A priori* estimates used in PID controller

- 500 Monte-Carlo runs
  - 2 cases camera measurement frequency:
    - 1 Hz
    - 10 Hz
  - Tension measurement frequency: 10 Hz



- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Simulation Parameters

Parameter	Value
Chaser Inertia Matrix J_C (kg-m^2)	diag$(83.3, 83.3, 83.3)$
Target Inertia Matrix J_T (kg-m^2)	diag$(15000, 3000, 15000)$
Chaser Mass m_C (kg)	500
Target Mass m_T (kg)	3000
Tether Young's Modulus E (Pa)	60×10^9
Tether Diameter d (m)	0.001
Tether Natural Length l_0 (m)	30
Tether Damping c (Ns/m)	16
Tether Attachment Point, Chaser $\boldsymbol{r}_{tp,C}$ (m)	$[0.5, 0, 0]^T$
Tether Attachment Point, Target $\boldsymbol{r}_{tp,T}$ (m)	$[0, -0.875, 0]^T$

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Outline

- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion

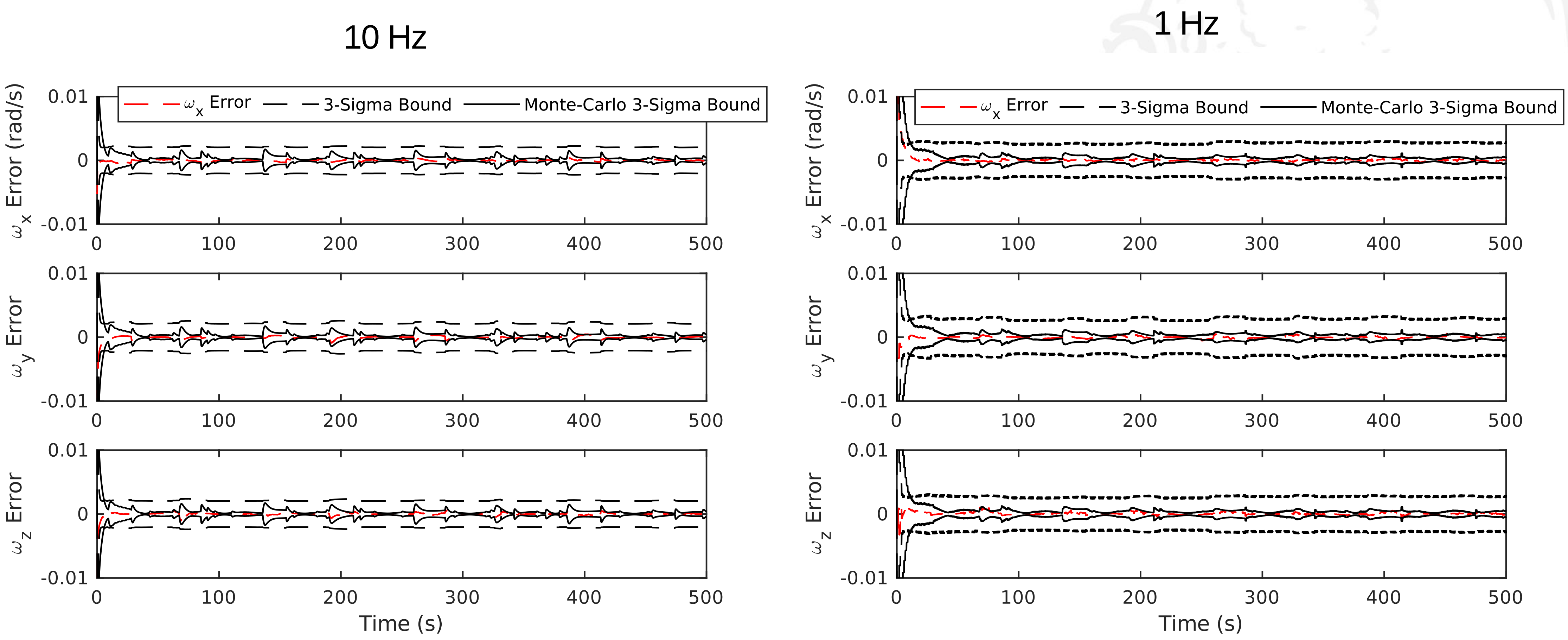
Estimation Performance

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Results: Angular Velocity

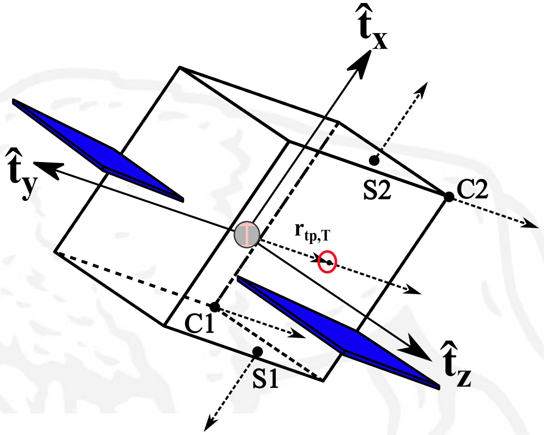
Accurate estimates in both cases

1 Hz causes slightly longer convergence time



- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

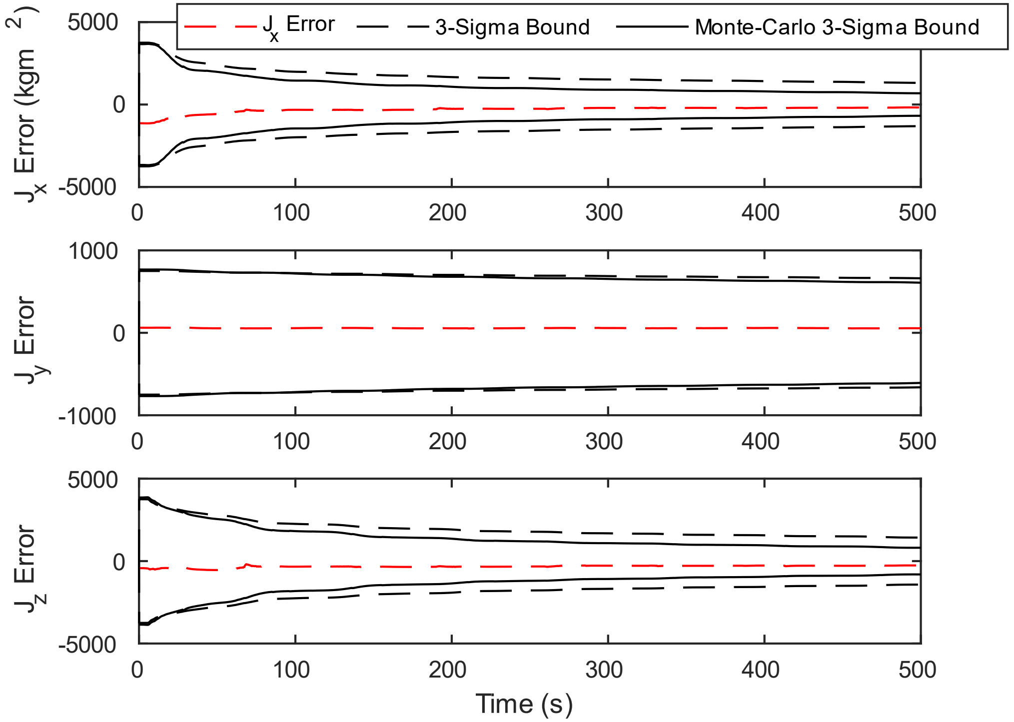
Results: Principal MMI Estimates



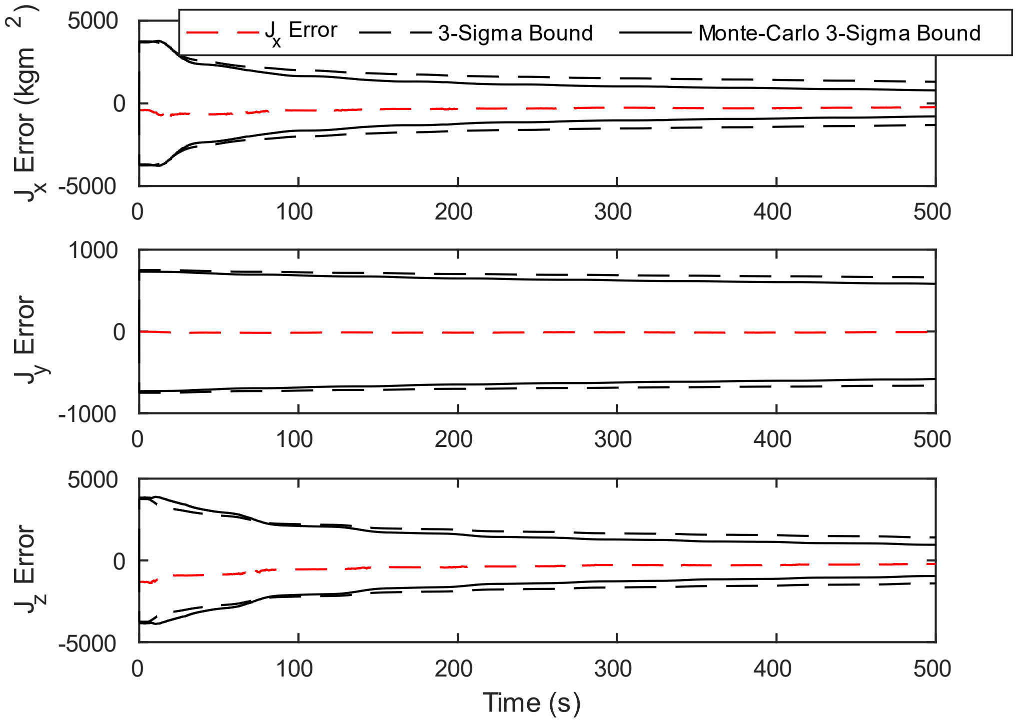
1 Hz:

- slightly longer convergence time
- uncertainty more closely matches statistics

10 Hz



1 Hz



- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Results: Final Principal MMI Estimates

Parameters	J_x	J_y	J_z
True Value (kg-m^2)	15000	3000	15000

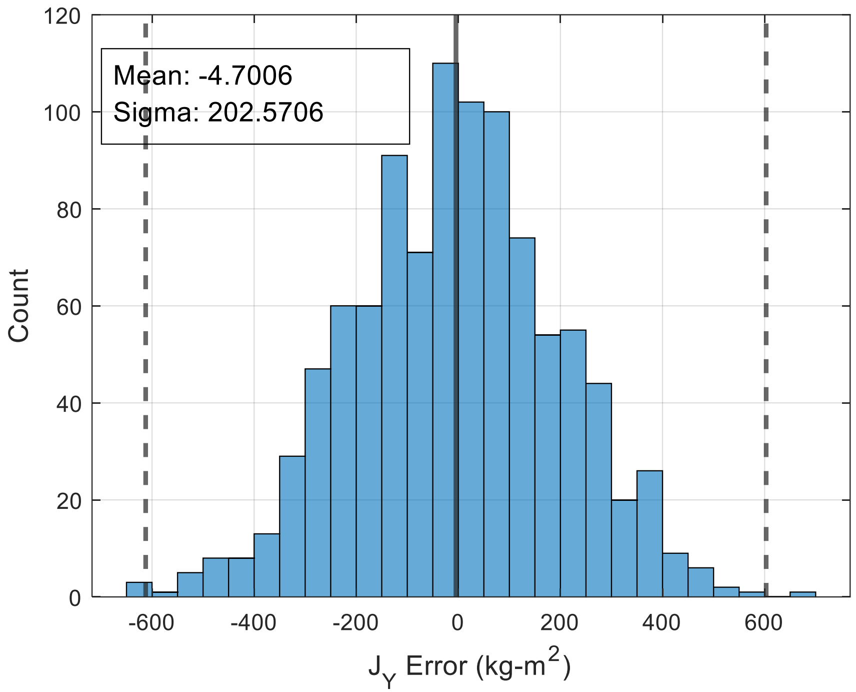
10 Hz

Parameters	J_x	J_y	J_z
Mean	0.23%	-0.15%	0.29%
STD	1.51%	6.75%	1.79%
99.73% Final Estimates	4.76%	20.40%	5.66%

1 Hz

Parameters	J_x	J_y	J_z
Mean	0.18%	-0.41%	0.21%
STD	1.75%	6.46%	2.12%
99.73% Final Estimates	5.43%	19.79%	6.57%

- Update frequency effect on final estimates is negligible
- Final estimate distribution is **normal**

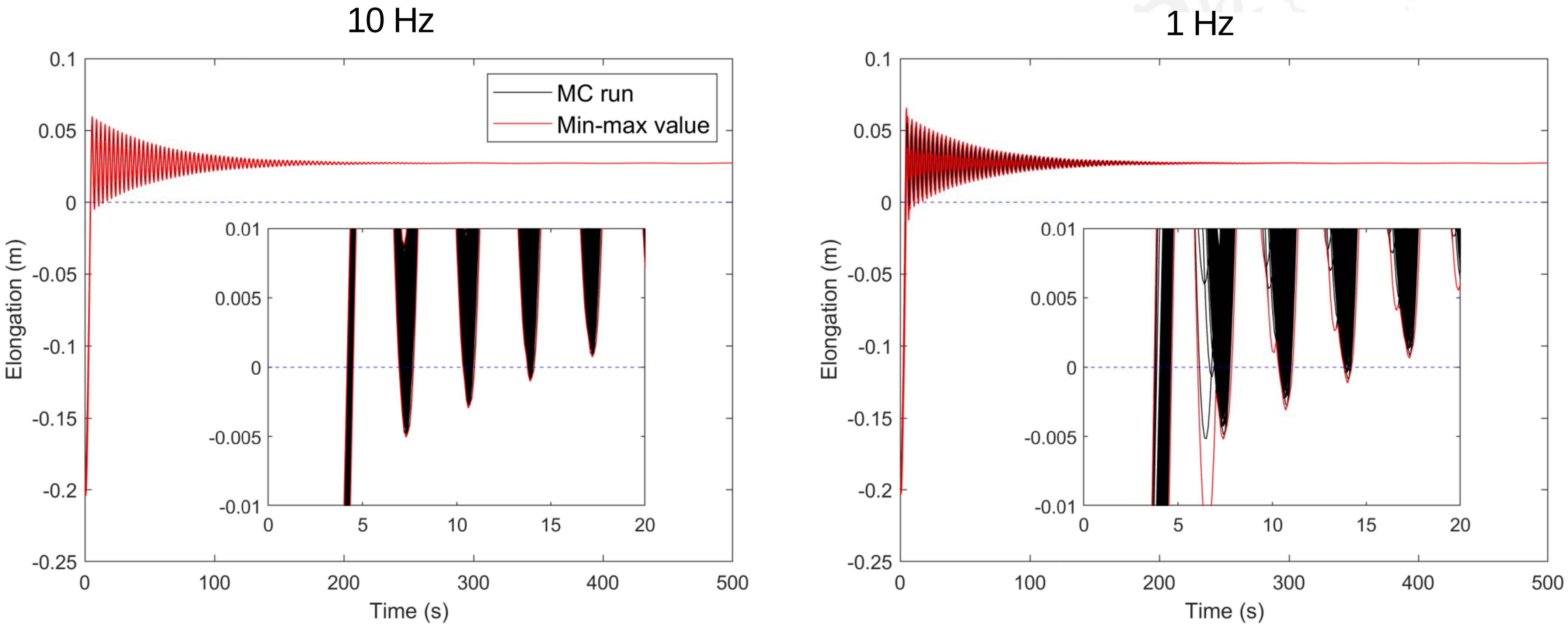


Control Performance

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Results: Elongation

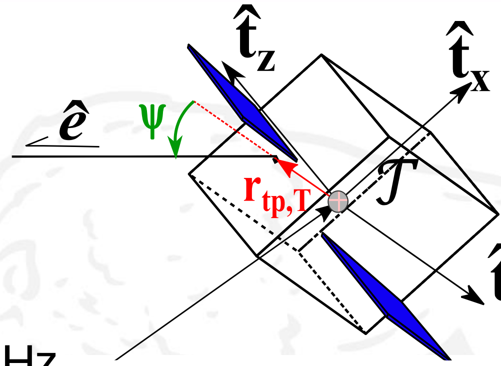
Control objective: Maintain safe post-capture operations



1 Hz has greater deviation prior to settling

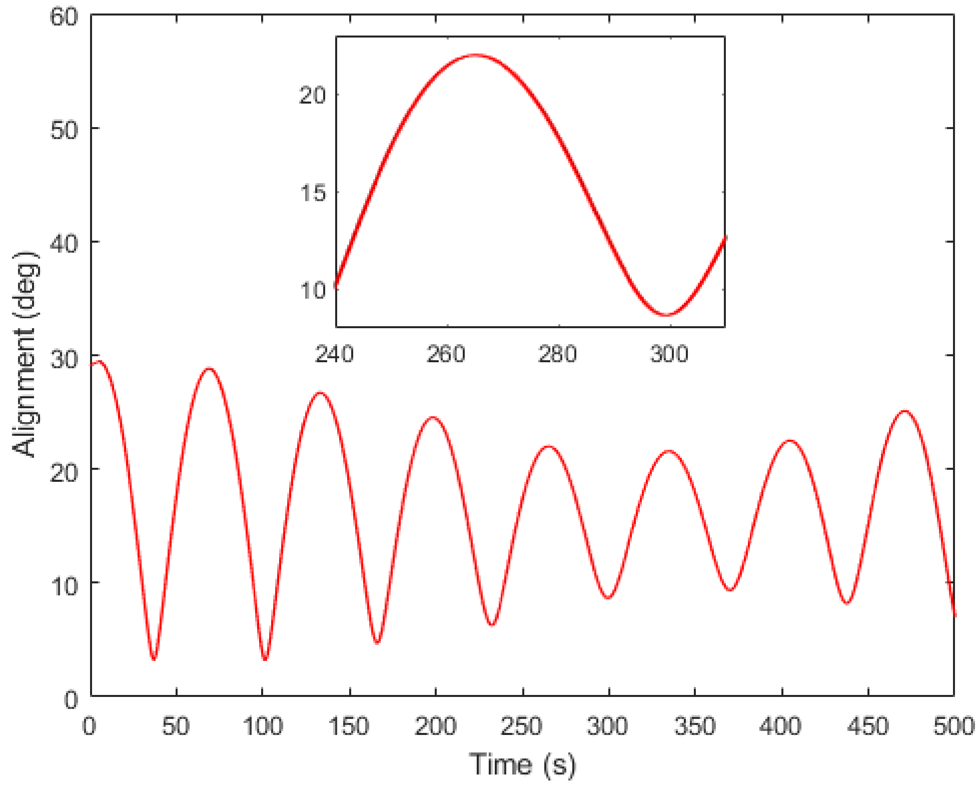
- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Results: Alignment Angle

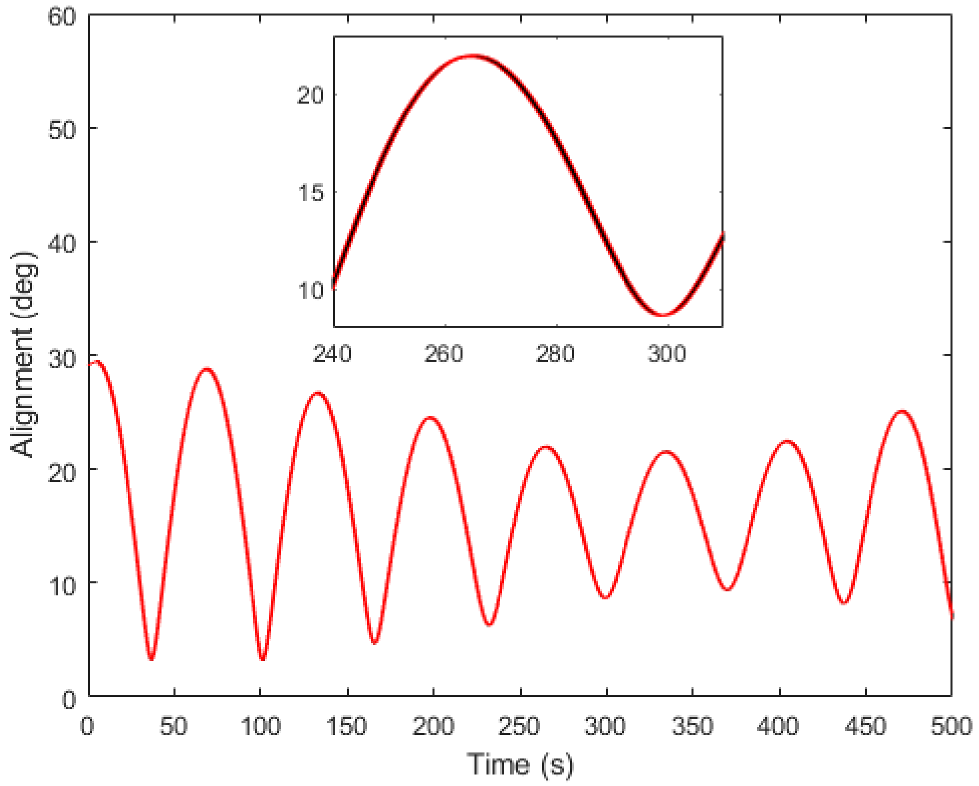


Safety is maintained (**alignment angle Ψ < 90°)**

10 Hz



1 Hz



- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Outline

- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Conclusion

- Separately developed control and estimation algorithms are now implemented together.
- Two different camera measurement frequencies investigated (1 Hz, 10 Hz).
- Estimation performance is minorly affected by frequency of measurements.
- Safe post-capture operations maintained with both measurement frequencies.

Future work

- Release additional required assumptions (e.g., known center of mass position)
- Modify controller type and control saturation limit

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

References

1. Field, L., Botta, E.M. “Relative Distance Control of Uncooperative Tethered Debris.” J Astronaut Sci 70, 55 (2023). https://doi.org/10.1007/s40295-023-00422-7
2. Bourabah, D., Gnam, C., and Botta, E.M. "Inertia tensor estimation of tethered debris through tether tracking." Acta Astronautica 212 (2023) https://doi.org/10.1016/j.actaastro.2023.08.021

- Outline
- Introduction
- Methodology
  - System Model
  - Estimation
  - Control
  - Parameters
- Performance
- Conclusion
- References

Thank you !

Questions?:

liamfiel@buffalo.edu

derekbou@buffalo.edu

ebotta@buffalo.edu

Funded by the National Science Foundation
Award# CRII: RI:2105011

Awarded NASA Space Grant Fellowship