Identification of Parameters for Tethered Satellite System to Emulate Net-Captured Debris Towing

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Introduction

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- **Increasing amounts of space debris** pose threats to spacecraft operations
- Many potential systems for Active Debris Removal have been proposed (Shan et al., 2017)
  - Harpoon-Based
  - Robotic-Arms-Based
  - Net-Based
- Tether-nets are particularly promising
  - ***Safe capture of large, tumbling objects***
- How can we study them?
  - **Simulation** and analysis

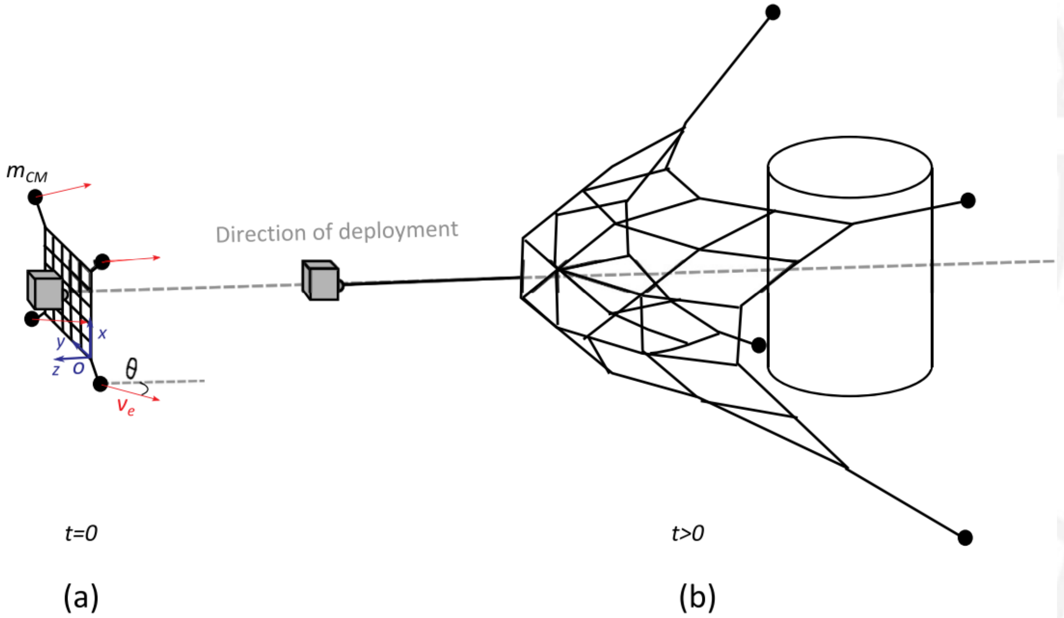
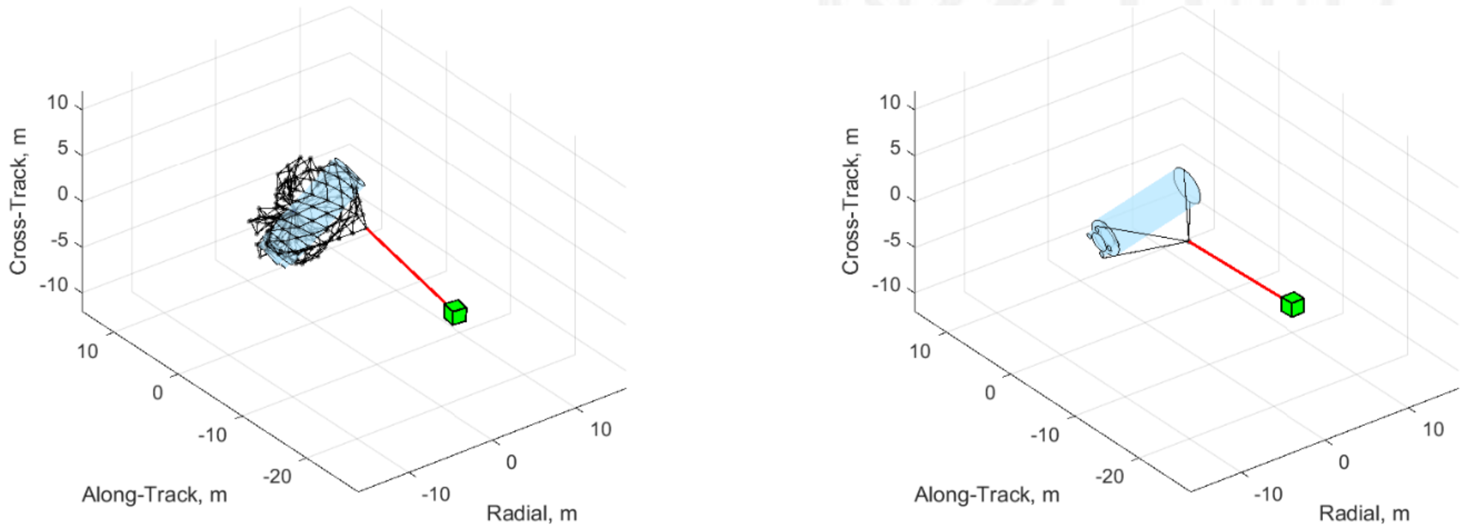


Fig. 1. Illustration of tether-net capture concept. (a): ejection. (b): configuration after deployment.

Figure from (Botta et al., 2019)

Introduction

- **Motivation:** Need a **simplified model** of the chaser-net-target system for long-duration orbital simulations.
  - High-fidelity simulations with net → ***very high computational cost***
- **Model Approximation:**
  - The net is replaced with ***4 tethers*** rigidly connected to the target.
  - Need to ***identify the appropriate properties*** of the sub-tethers (STs) + tethers connection point mass of the lower-order model that ***best represent*** the high-fidelity dynamics.

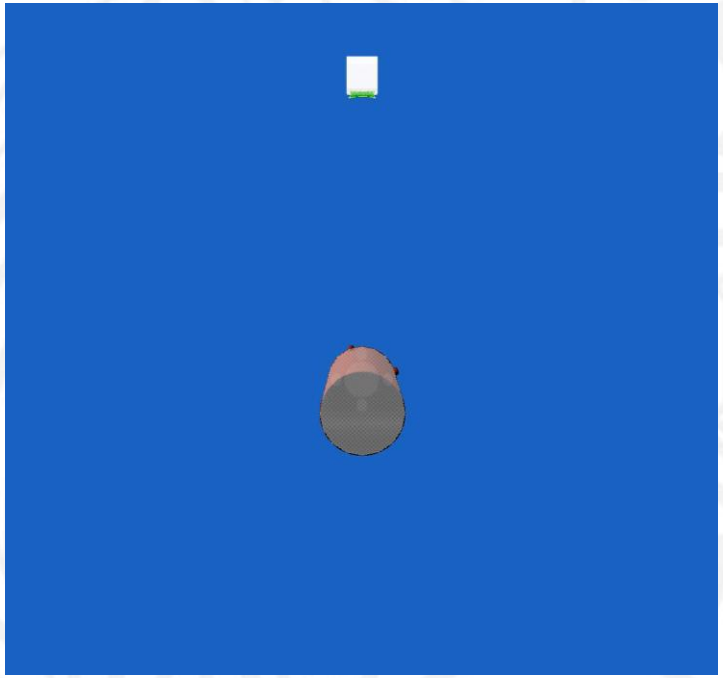


Systems Description and Modeling

Net Capture System and Target Debris

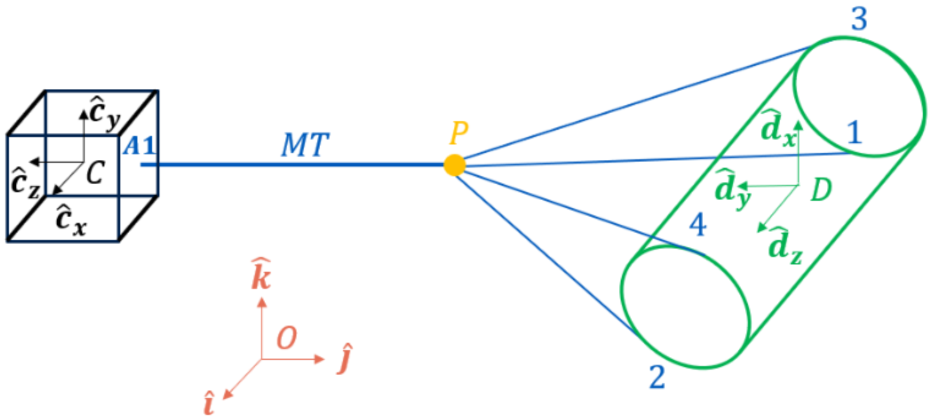
- Net modeled via the **lumped-parameter modeling method**
  - ***Computational challenge:*** The entire system often involves ***1000+ degrees of freedom***
- **Corner masses** used to guide the net to the target.
- Net includes a **closing mechanism,** attached to the chaser by the **main tether (MT) and winch.**
- Sliding-mode **attitude controller** present on the cubic chaser to maintain desired orientation.
- **Target debris:** Zenit-2 rocket upper stage

Net simulator detailed within (Botta et al., 2019)



Sub-Tether Tethered Satellite System

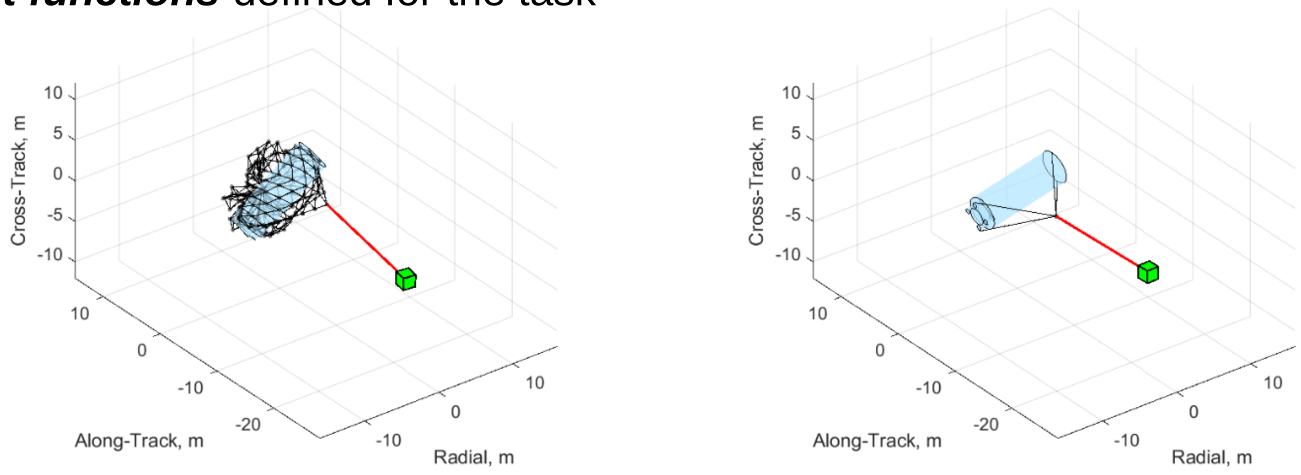
- Chaser and debris are **rigid bodies** with the same dimensions as with the high-fidelity model.
- All tethers modeled as nonlinear spring-damper **(Kelvin–Voigt)** elements.
  - MT is given the ***same length, stiffness, and damping properties*** as with the high-fidelity model.
- Connection point P links the ***MT to the 4 STs.***
  - Modeled as a point mass
- Sliding-mode **attitude controller** present on the cubic chaser to maintain desired orientation.



Parameter Identification

Parameter Identification

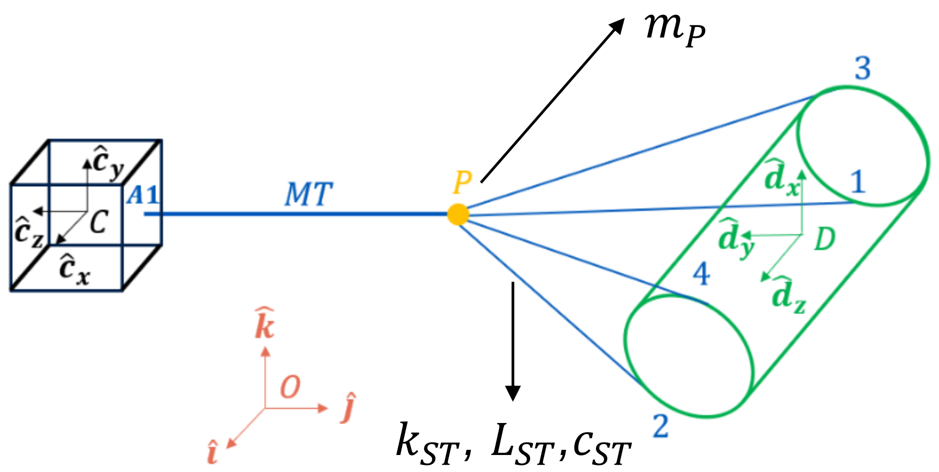
- **Parameter Identification Process:**
  - Perform **6 high-fidelity** debris towing simulations
    - ***3 for parameter identification*** via solving optimization problems.
    - ***3 for validation*** of the parameters on unseen data.
    - Use all same initial conditions, except for ***initial target angular velocity.***
  - Perform **optimization** to determine the lower-order model parameters which **minimize dynamics difference** with the high-fidelity model.
    - ***2 cost functions*** defined for the task



Design Variables

- Thread stiffness of the STs: $s_1 = \log_{10}(k_{ST})$
  - $1 \leq s_1 \leq 4$
- Thread length of the STs: $s_2 = L_{ST}, \mathrm{m}$
  - $6 \leq s_2 \leq 16$
- Thread damping of the STs: $s_3 = \log_{10}(c_{ST})$
  - $0 \leq s_3 \leq 4$
- Percent of Net Mass Distributed to the Connection Point: $m_P = s_4 m_{net}, \mathrm{kg}$
  - Rest of the net mass distributed to the target:
    - $\mathrm{m_{target}} = \mathrm{m_{target,0}} + (1 - \mathrm{s_4})\mathrm{m_{net}}, \mathrm{kg}$
  - $0.1 \leq s_4 \leq 1$

- Bounds to **limit the search space** of the optimization.
  - Chosen based on values the parameters are expected to lie within.
- Stiffness and damping parameters of the STs **scaled by** $\log_{10}()$ **functions** → allow values to be of similar magnitude to other parameters.
  - To aid the optimization solver in finding solutions.



Cost Functions

$(.)^{\mathcal{H}}$: **High-fidelity model quantities**
$(.)^{\mathcal{L}}$: **Lower-order model quantities**

- **Cost Function 1:** Difference in (i) chaser-debris relative position, (ii) debris angular velocity, and (iii) chaser angular velocity between models.

$$\boldsymbol{r}^{\mathcal{H}}_{D/C} = \boldsymbol{r}^{\mathcal{H}}_{D/O} - \boldsymbol{r}^{\mathcal{H}}_{C/O}$$

$$\boldsymbol{r}^{\mathcal{L}}_{D/C} = \boldsymbol{r}^{\mathcal{L}}_{D/O} - \boldsymbol{r}^{\mathcal{L}}_{C/O}$$

$$\boldsymbol{r}_{\Delta} = \boldsymbol{r}^{\mathcal{L}}_{D/C} - \boldsymbol{r}^{\mathcal{H}}_{D/C}$$

$$\boldsymbol{\omega}_{C,\Delta} = ({}^{\mathcal{O}}\boldsymbol{\omega}^{C})^{\mathcal{L}} - ({}^{\mathcal{O}}\boldsymbol{\omega}^{C})^{\mathcal{H}}$$

$$\boldsymbol{\omega}_{D,\Delta} = ({}^{\mathcal{O}}\boldsymbol{\omega}^{D})^{\mathcal{L}} - ({}^{\mathcal{O}}\boldsymbol{\omega}^{D})^{\mathcal{H}}$$

$$f_1(\boldsymbol{s}) = \sum_{j=1}^{3} w_1 \mathrm{RMSE}_{r,j} + w_2(\mathrm{RMSE}_{\omega_D,j} + \mathrm{RMSE}_{\omega_C,j})$$

$$\mathrm{RMSE}_{r,j} = \sqrt{\sum_{g=1}^{N} \frac{||\boldsymbol{r}_{\Delta,j,g}||^2}{N}}$$

$$\mathrm{RMSE}_{\omega_D,j} = \sqrt{\sum_{g=1}^{N} \frac{||\boldsymbol{\omega}_{D,\Delta,j,g}||^2}{N}}$$

$$\mathrm{RMSE}_{\omega_C,j} = \sqrt{\sum_{g=1}^{N} \frac{||\boldsymbol{\omega}_{C,\Delta,j,g}||^2}{N}}$$

- **Cost Function 2:** Difference in the MT tension between models.
  - MT tensions ***dependent on the relative dynamics*** → may indirectly enable the relative dynamics to be as identical as possible.

$$f_2(\boldsymbol{s}) = \sum_{j=1}^{3} \mathrm{RMSE}_{T,j}$$

$$\mathrm{RMSE}_{T,j} = \sqrt{\sum_{g=1}^{N} \frac{(T^{\mathcal{H}}_j - T^{\mathcal{L}}_j)^2}{N}}$$

Optimization Problem Formulation

$$\min_{\boldsymbol{s}} f_k\,(\boldsymbol{s})$$
$$\text{where: } \boldsymbol{s} = [s_1, s_2, s_3, s_4], k = 1, 2$$
$$s_{j,LB} \le s_j \le s_{j,UB}$$

Chosen Solver →

- **Mesh Adaptive Direct Search (MADS)**
  - Derivative-free optimization solver
  - Utilized in many scientific and engineering application
    - (Alarie et al., 2021)
  - Requires an initial guess to be given

- **Notes:**
  - Do not know the shapes of the cost functions
    - Likely ***nonconvex*** with respect to the design variables
    - ***Gradients unknown***
  - Nonlinear programming problem
  - No constraints given on the value of the cost functions
    - Only upper and lower bounds given to design variables

Analysis of Results

Converged Optimization Results

- **Converged design variables differ** based on the choice of initial guesses.
  - ***More drastic change using Cost Function 2*** compared to 1 for different initial guess.

Converged Cost Function Values for Training Dataset

Obj. Function	Initial Guess 1	Initial Guess 2	Initial Guess 3	Initial Guess 4	Initial Guess 5
$f_1(s)$	10.3854	10.3915	10.3824	10.3853	10.3859
$f_2(s)$	272.03	292.99	292.46	272.15	292.818

Best Converge Cost Function 1 value and design variables

Converged Decision Variables Using $f_1(s)$

Variables	Initial Guess 1	Initial Guess 2	Initial Guess 3	Initial Guess 4	Initial Guess 5
s_1	1.3942	1.3932	1.3948	1.3943	1.3943
s_2	6.5288	6.5180	6.5406	6.5281	6.5282
s_3	1.3114	1.3058	1.3257	1.3145	1.3131
s_4	0.5602	0.7534	0.2726	0.5546	0.5832

Best Converge Cost Function 2 value and design variables

Converged Decision Variables Using $f_2(s)$

Variables	Initial Guess 1	Initial Guess 2	Initial Guess 3	Initial Guess 4	Initial Guess 5
s_1	2.7398	1.0409	2.5097	2.7454	1.1012
s_2	8.5805	9.1683	6.5366	8.6522	9.1923
s_3	2.1721	2.8961	2.3678	2.1952	2.8975
s_4	1.0000	0.5933	0.3817	0.1608	0.1371

Converged Optimization Results

- **Converged design variables differ** based on the choice of initial guesses.
  - ***More drastic change using Cost Function 2*** compared to 1 for different initial guess.
- Evaluating **cost functions using validation dataset + converged design variables** yielded similar costs.

Cost Function Values for Validation Dataset

Obj. Function	Initial Guess 1	Initial Guess 2	Initial Guess 3	Initial Guess 4	Initial Guess 5
$f_1(s)$	11.8821	11.8982	11.8601	11.8814	11.8826
$f_2(s)$	293.37	287.97	326.78	290.73	288.55

Best Converge Cost Function 1 value and design variables

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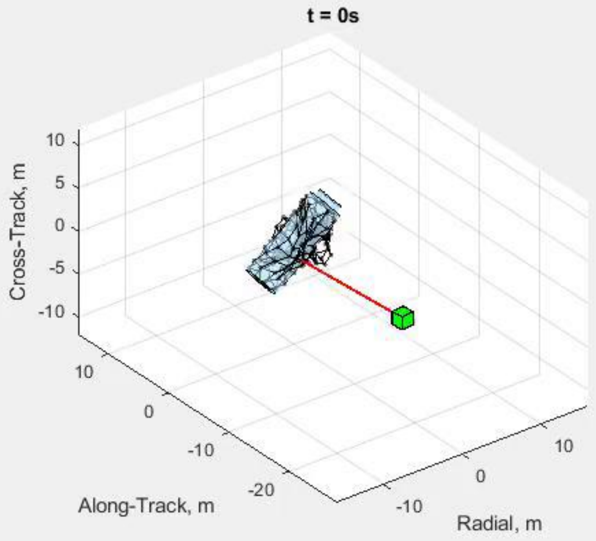
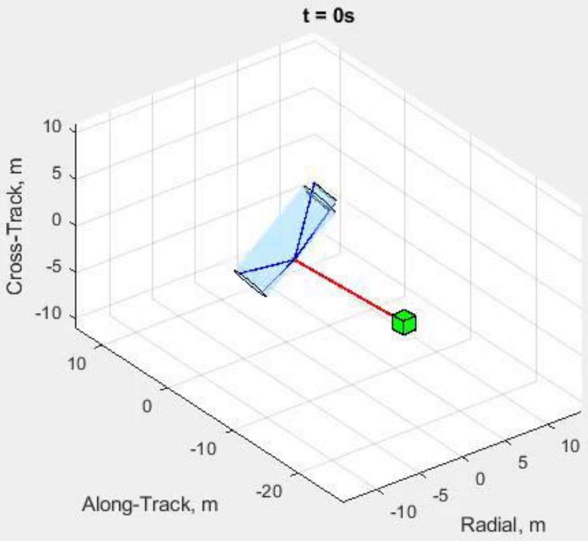
Sample Scenario Comparison

- Overall **dynamics similar** between the models
  - Chaser attitude in the high-fidelity model ***less stabilized*** than in the lower-order simulations

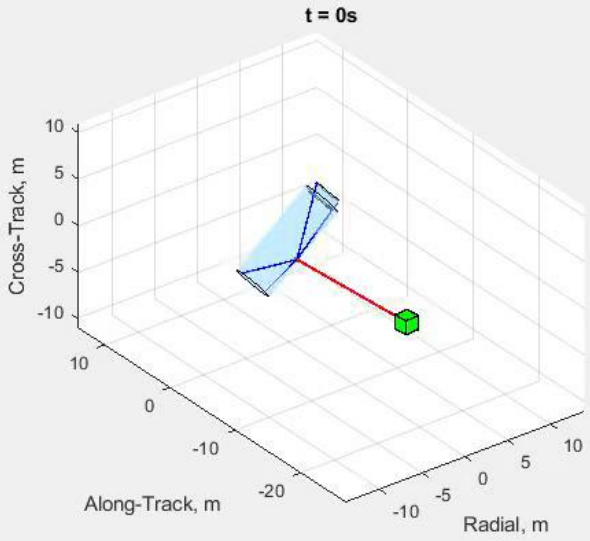
High-Fidelity Full-Net System



ST System With Parameters Obtained From Best Cost Function 1 Optimization



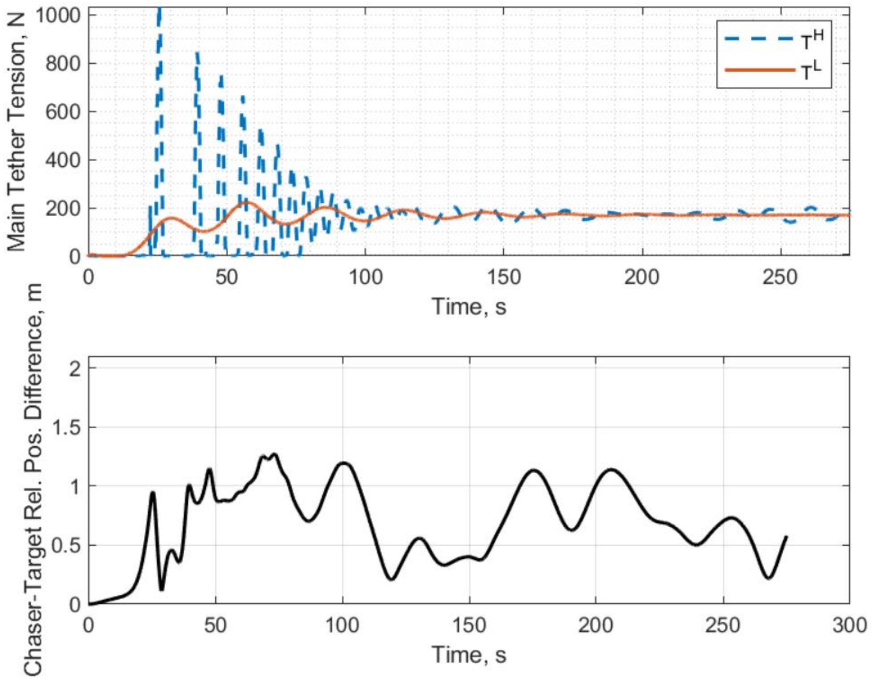
ST System With Parameters Obtained From Best Cost Function 2 Optimization



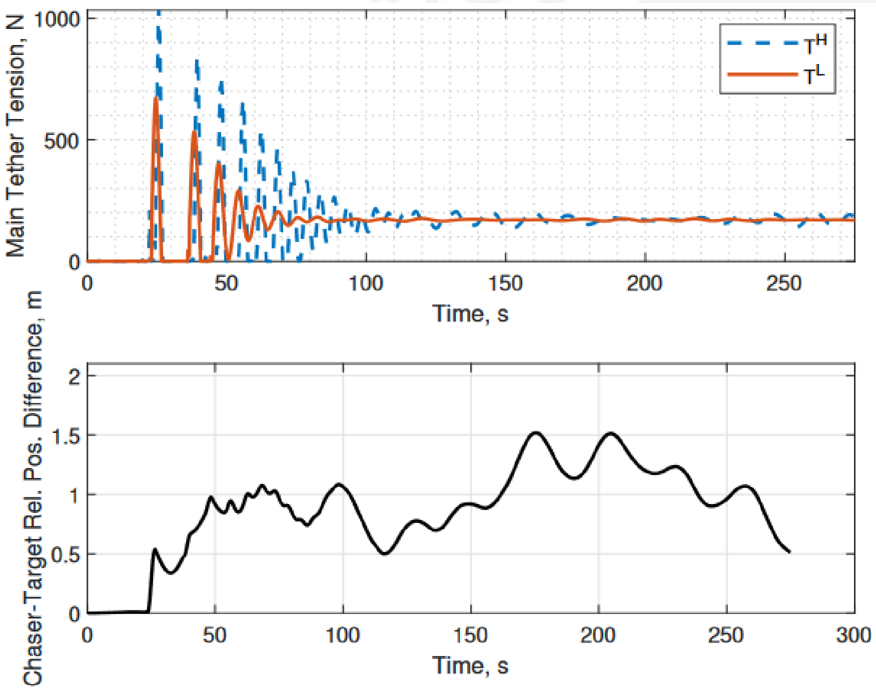
Sample Scenario Comparison

- Overall **dynamics similar** between the models
  - Parameters from Cost Function 1 results in ***better relative dynamics matching***; Cost Function 2 results in ***better MT tension matching.***

High vs. Low Fidelity: ST System With Parameters Obtained From Best Cost Function 1 Optimization



High vs. Low Fidelity: ST System With Parameters Obtained From Best Cost Function 2 Optimization



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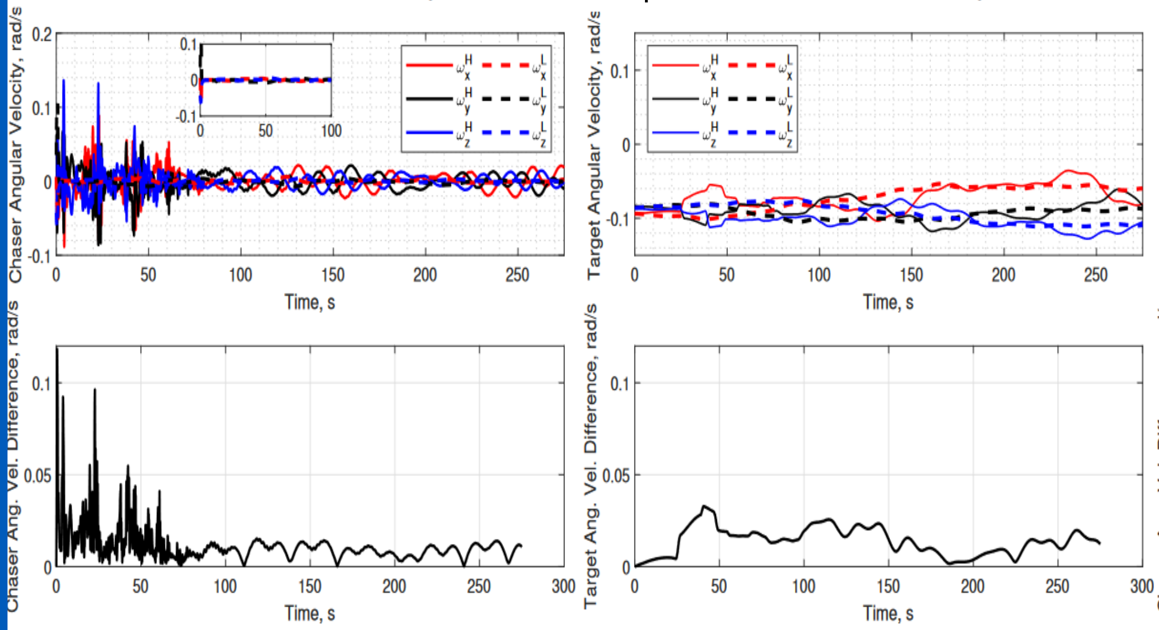
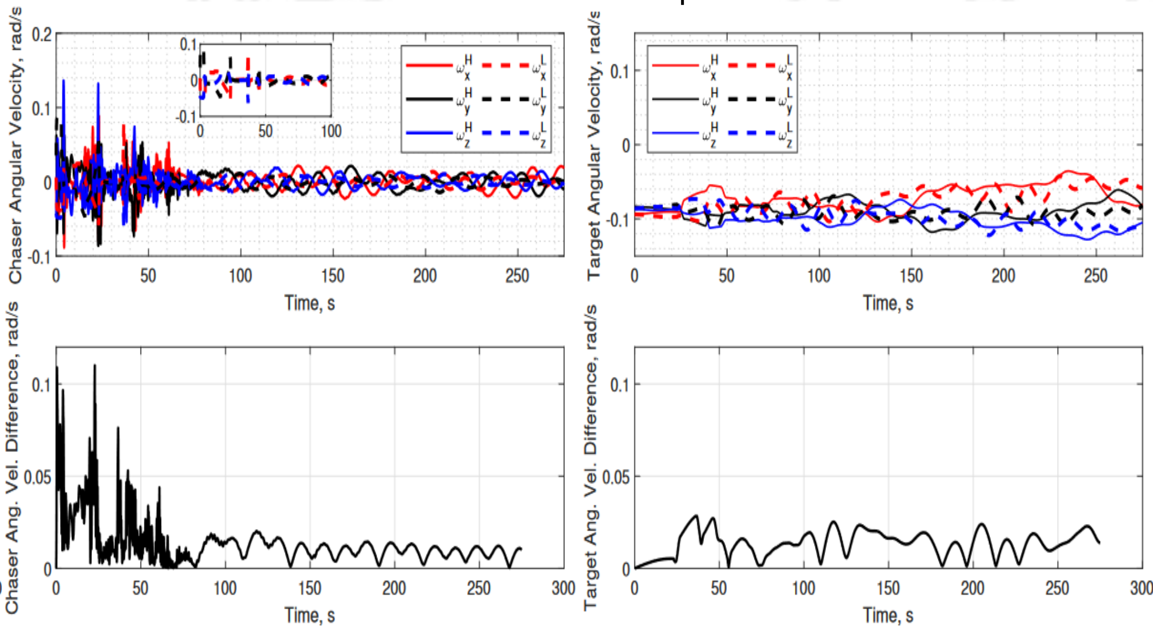
Sample Scenario Comparison

- Overall **dynamics similar** between the models
  - High-fidelity ***chaser attitude dynamics is less stabilized*** compared to both lower-order simulations.
  - Using parameters from Cost Function 1 results in ***better debris angular rates matching.***

High vs. Low Fidelity: ST System With Parameters Obtained From Best Cost Function 1 Optimization



High vs. Low Fidelity: ST System With Parameters Obtained From Best Cost Function 2 Optimization



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- **Parameter identification framework** proposed to allow lower-order TSS model to best approx. net-based debris towing.
- **Two optimization cost functions** were formulated to **minimize the difference in dynamics quantities** of interest between models.
  - Lower-order TSS with determined parameters demonstrated ***satisfactory dynamics matching performance***.
- Compared to Cost Function 2, Cost Function 1 demonstrated:
  - **Less sensitivity to initial guesses**
  - **Better overall dynamics matching** (except MT tension).
- **Future work:** Apply the framework to larger datasets with **larger variations** in the simulation's initial conditions.

References

- Shan, Minghe, Jian Guo, and Eberhard Gill. "Review and comparison of active space debris capturing and removal methods." *Progress in Aerospace Sciences* 80 (2016): 18-32.
- Botta, E. M., Sharf, I., and Misra, A. K., “Simulation of tether-nets for capture of space debris and small asteroids,” Acta Astronautica, Vol. 155, (2019), pp. 448–461.
- Alarie, Stéphane, Charles Audet, Aïmen E. Gheribi, Michael Kokkolaras, and Sébastien Le Digabel. "Two decades of blackbox optimization applications." EURO Journal on Computational Optimization 9 (2021): 100011.

Thank you!

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Systems Parameters and Initial Conditions

System Parameters For Both High-Fidelity and Lower-Order Simulations

Variables	Value	Units
Chaser Mass, m_C	1600	kg
Nominal Debris Mass, m_D	9000	kg
Chaser Side Length, L_C	1.5	m
Debris Length, L_D	11	m
Debris Diameter, d_D	3.9	m
Chaser Inertia Matrix, J_C	diag(266.67, 266.67, 266.67)	kgm^2
Debris Inertia Matrix, J_D	diag(94880, 94880, 46295.5)	kgm^2
Chaser Attachment Point, $[\boldsymbol{r}_{A1/C}]_C$	$[0, 0, -0.75]^T$	m
Debris Attachment Point 1, $[\boldsymbol{r}_{1/D}]_D$	$[-1.9500, 0, -5.7170]^T$	m
Debris Attachment Point 2, $[\boldsymbol{r}_{2/D}]_D$	$[-1.9500, 0, 5.2830]^T$	m
Debris Attachment Point 3, $[\boldsymbol{r}_{3/D}]_D$	$[1.9500, 0, -5.7170]^T$	m
Debris Attachment Point 4, $[\boldsymbol{r}_{4/D}]_D$	$[1.9500, 0, 5.2830]^T$	m
Main-tether Stiffness, k_{MT}	3000	N/m
Main-tether Damping, c_{MT}	300	Ns/m
Main-tether Natural Length, l_{MT}	15.0	m
Time for chaser thrust to reach maximum, t_{slope}	50	s

Initial Conditions For the High Fidelity Simulations

Variables	Value	Units
$\boldsymbol{r}_{C/O}$	$[4.95199, -1.0547469, -4.65022589]^T \times 10^6$	m
${}^{\mathcal{O}}\boldsymbol{v}_{C/O}$	$[4.771333506, 4.267936104, 4.119936176]^T \times 10^3$	m/s
$\boldsymbol{q}_C$	$[0.506372, 0.628113, -0.5865386, -0.0709467]^T$	-
${}^{\mathcal{O}}\boldsymbol{\omega}^C$	$[-0.0085526588, 0.019837, 0.0020484]^T$	rad/s
$\boldsymbol{r}_{D/O}$	$[4.952002, -1.054735, -4.650215]^T \times 10^6$	m
${}^{\mathcal{O}}\boldsymbol{v}_{D/O}$	$[4.771338, 4.267935, 4.1199337]^T \times 10^3$	m/s
$\boldsymbol{q}_D$	$[\ 0.3834407, 0.4526303, 0.7957778, 0.12180569]^T$	-
${}^{\mathcal{O}}\boldsymbol{\omega}^D$	$\lvert\lvert {}^{\mathcal{O}}\boldsymbol{\omega}^D(0) \rvert\rvert \cdot [0.0047695, -0.9999851, 0.002652839]^T$	rad/s
$\boldsymbol{r}_{P/O}$	$[4.951991, -1.05474644, -4.6502254]^T \times 10^6$	m
${}^{\mathcal{O}}\boldsymbol{v}_{P/O}$	$[4.771333506, 4.267936104, 4.119936176]^T \times 10^3$	m/s

Converged Optimization Results

- Provided Initial Guess

List of Initial Decision Variables Given to The Optimization Solver

Variables	Initial Guess 1	Initial Guess 2	Initial Guess 3	Initial Guess 4	Initial Guess 5
s_1	3	2	3	3	3
s_2	9	9	8	9	9
s_3	1	1	1	2	1
s_4	0.5	0.5	0.5	0.5	0.75

- Best converged design variables are converted and displayed as physical parameters below:

Parameter	$f_1(s)$	$f_2(s)$
k_{ST},N/m	24.819	549.28
l_{ST}, m	6.5406	8.5805
c_{ST}, Ns/m	21.169	148.627
m_p, kg	0.7449	2.7326

- Initial Debris Angular Speed for different simulations:

Simulation #	$\|\|{}^{\mathcal{O}}\omega^{\mathcal{D}}(0)\|\|$
1	0.16654 rad/s
2	0.16151 rad/s
3	0.15985 rad/s
4	0.15301 rad/s
5	0.14948 rad/s
6	0.14622 rad/s