ICTIS 2024 CONFERENCE PROCEEDINGS

The Seventh International Conference on Tethers in Space

3rd June 2024-5th June 2024
Lassonde School Of Engineering, York University
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THE SEVENTH INTERNATIONAL CONFERENCE ON TETHERS IN SPACE

(June 3rd, 2024)

ABSTRACT

Session 1 - Space Net

Chair: Prof. George Zhu

- **Title:** Identification of Parameters for Tethered Satellite System to Emulate Net-Captured Debris Towing (2024080)
- **Title:** Theoretical Modeling and Analysis of the Launching Process in an Electromagnetic Coil Launcher (2024075)
- **Title:** Suppression of Tether-Net Shrinking Motion Using Double-linked Bullet (2024032)
- **Title:** Cooperative Game Theory Based Formation Control for Tethered Space Net Robot (2024019)
- **Title:** Deployment and Descending Dynamics of a Large-Scale Tether-Net for Asteroid Touchdown Missions (2024071)

Paper No: 2024080
7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

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

A. Boonrath[1], T. Singh[2], E. M. Botta[3]
1 Ph.D. Student, Department of Mechanical and Aerospace Engineering, University at Buffalo, Buffalo, NY, 14260, USA, achirabo@buffalo.edu
2 Professor, Department of Mechanical and Aerospace Engineering, University at Buffalo, Buffalo, NY, 14260, USA, tsingh@buffalo.edu
3 Assistant Professor, Department of Mechanical and Aerospace Engineering, University at Buffalo, Buffalo, NY, 14260, USA, ebotta@buffalo.edu

Conference Topic: Mathematical Modelling of Space Tethers, Dynamics, Controls

Tethered nets – relatively lightweight and allowing to capture large, rotating pieces of debris from a safe distance – have a high potential for success in conducting Active Debris Removal (ADR) missions [1,2]. Due to their low-medium technological readiness level (TRL), however, tether-net systems must be further studied before large-scale missions to capture uncooperative objects in space can be performed. High-fidelity net-based simulations are typically very computationally costly and may be prohibitive for detumbling and deorbiting simulations of uncooperative debris, due to the large number of degrees of freedom (DoFs) required to model the dynamics of the net [3]. To reduce the computational cost, a lower-order model can be employed, in which the net-wrapped debris is replaced by a tethered satellite system (TSS) in which debris is rigidly attached to 4 sub-tethers (STs) that extend from the main-tether (MT). This work aims to determine the length, stiffness, and damping properties of the 4 STs (assumed the same for all STs) and the mass of the connection point that links the STs to the MT (for a total of 4 design variables), such that the dynamics of the lower-order system match that of the net-based high-fidelity simulation as much as possible.

The debris of interest for the net-based capture in this work is the second stage of the Zenit 2 launch vehicle, which is one of the most wanted debris in orbit [5]. A cubic chaser spacecraft is employed to transport the tether-net system close to the target and deorbit the debris. The net component of the system consists of a square net with four corner masses (CMs) attached to each corner of the net. The net is deployed by shooting the CMs toward the target. To ensure that the net remains around the debris after wrapping, threads laced through the four CMs and eight nodes along the net's perimeter are employed as a closing mechanism. After a predetermined amount of time since the net wraps around the target, the chaser's thruster activates to change the coupled system's orbital velocity.

Vortex Studio, a multi-body dynamics simulation platform, is utilized to perform high-fidelity simulations of net-based ADR missions [4] (see Fig. 1). The lumped-parameter modeling method discretizes the net's mass into spherical rigid bodies (called *nodes*); the nodes are placed at the net's thread intersections and at the CMs. The nodes (and all other rigid bodies in simulation) are given contact materials and collision geometries to model the contact dynamics with other objects. Forces due to friction and normal to the contact surface are computed via the scaled-box friction model (an approximation based on Coulomb's friction) and a modified continuous compliant model, respectively [4]. In simulation, the nodes are linked together via *distance joints.* The MT links the net's central node to the chaser and is modeled similarly to the threads of the net.

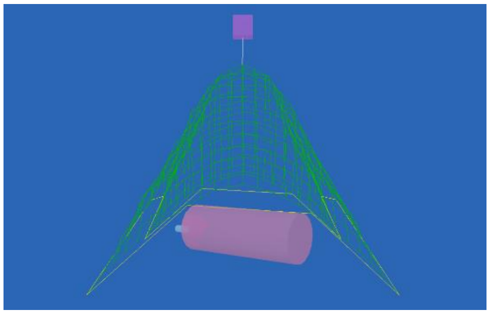

Figure 1. Tether-Net System for ADR Mission Mid-Deployment

The reduced-order TSS model consists of the chaser and debris, both modeled as cubic rigid bodies with DoFs, and the connection point that links the MT to the STs (modeled as a point mass with 3 DoFs). The system is visualized in Fig. 2, where the inertial ECI reference frame $I = \{O, \hat{\boldsymbol{I}}, \hat{\boldsymbol{J}}, \hat{\boldsymbol{K}}\}$ is labeled in red. The chaser and the debris body frame axes $C = \{C, \hat{\boldsymbol{c}}_x, \hat{\boldsymbol{c}}_y, \hat{\boldsymbol{c}}_z\}$ and $D = \{D, \hat{\boldsymbol{d}}_x, \hat{\boldsymbol{d}}_y, \hat{\boldsymbol{d}}_z\}$ are colored in black and green, respectively. Both the MT and the STs are modeled as Kelvin-Voigt elements. The MT is rigidly attached at the center of the face of the chaser that is facing the debris, while the STs are rigidly attached to the 4 corners of the debris that are facing the chaser. The orbital dynamics simulation of the TSS is conducted using MATLAB's *ode45* integration scheme. The dynamics of this TSS configuration has been explored in the past by multiple authors [6,7,8] and it was found that the system has the capability to detumble the towed debris because of the visco-elastic properties of the tethers.

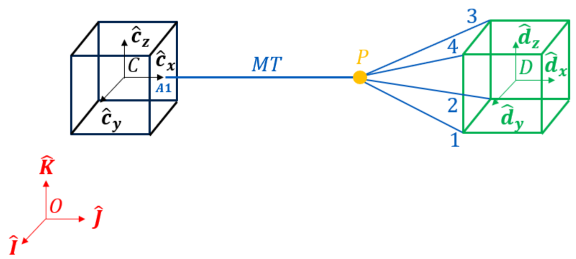

Figure 2. Model of TSS with 4 STs

Considering the nonlinearities in modeling of the TSS, an optimization problem is set up for system identification, of which the objective is to minimize the difference in the simulated dynamics over time between the net-based high-fidelity and lower-order TSS models:

$$\min_{\mathbf{S}} f_k(\mathbf{S})$$

$$s_{j,LB} \leq s_j \leq s_{j,UB}$$

$$\text{where: } \mathbf{S} = [s_1, s_2, s_3, s_4]^T$$

where $f_k(\mathbf{S})$ indicates the cost function that is being optimized, $\mathbf{S}$ is the vector of 4 design variables, and $s_{j,LB}$ and $s_{j,UB}$ are the lower and upper bounds of the j-th design variable. This work explores the use of two cost functions to perform the parameter identification, each utilizing the Root Mean Square Error (RMSE) between select dynamics quantities of interest. The RMSE will account for multiple simulations, each using unique initial conditions to allow the optimization problem to consider multiple possible scenarios. In the first cost function, $f_1(\mathbf{S})$, the goal is to minimize the weighted sum of the relative distance and of the relative angular velocity between the chaser and the target. Cost function 1 is expressed mathematically as:

$$f_1(\boldsymbol{S}) = \sum_{i=1}^{N} \mathrm{w}_1 \mathrm{RMSE}_{\mathrm{Pos,i}} + \mathrm{w}_2 \mathrm{RMSE}_{\mathrm{Ang,i}}$$

In the expression above, N is the total number of simulations considered, w_1 and w_2 are the weights given to RMSE quantities regarding relative position and angular velocity, respectively. These dynamics quantities are chosen because they relate to the safety and success of ADR missions in which the target is uncooperative. The second cost function, $f_2(\mathbf{S})$, returns the RMSE of the tension in the MT between high-fidelity and lower-order models. Cost function 2 is expressed mathematically as:

$$f_2(\boldsymbol{S}) = \sum_{i=1}^{N} \mathrm{RMSE}_{\mathrm{T,i}}$$

This quantity is chosen since minimizing differences in the tension may indirectly influence all states of the debris and chaser to be as identical as possible, due to the tension in the MT depending on the relative dynamics between the rigid bodies.

The optimization problem can be classified as a Nonlinear Programming Problem (NLP) as result of the non-linearities, with multiple possible local minima. As such, functions within MATLAB's Global Optimization Toolbox – such as *patternsearch()* – will be used to solve the optimization problem. The final manuscript will present optimal design parameters obtained utilizing both $f_1(\mathbf{S})$ and $f_2(\mathbf{S})$. Plots of the dynamics quantities over time for both the high-fidelity and lower-order modeling will also be provided for analysis.

References

[1] Shan, M., Guo, J., and Gill, E., "A Review and comparison of active space debris capturing and removal methods," *Progress in Aerospace Sciences*, Vol. 80, 2015, pp. 18–32. https://doi.org/10.1016/j.paerosci.2015.11.001.

[2] Ledkov, A., and Aslanov, V., "Review of contact and contactless active space debris removal approaches," *Progress in Aerospace Sciences*, Vol. 134, 2022, p. 100858. https://doi.org/10.1016/j.paerosci.2022.100858.

[3] Boonrath, A., and Botta, E. M., "Validation of Models for Net Deployment and Capture Simulation with Experimental Data," *Journal of Spacecraft and Rockets*, 2023, pp. 1–19. https://doi.org/10.2514/1.A35798

[4] 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. https://doi.org/10.1016/j.actaastro.2018.07.046

[5] McKnight, D., Witner, R., Letizia, F., Lemmens, S., Anselmo, L., Pardini, C., Rossi, A., Kunstadter, C., Kawamoto, S., Aslanov, V., et al., "Identifying the 50 statistically-most-concerning derelict objects in LEO," *Acta Astronautica*, Vol. 181, 2021, pp.282–291. https://doi.org/10.1016/j.actaastro.2021.01.021.

[6] Yang, Keying, et al. "Dynamics of a debris towing system with hierarchical tether architecture." *Acta Astronautica* 177 2020: 891-905. https://doi.org/10.1016/j.actaastro.2019.10.048

[7] Shan, Minghe, and Lingling Shi. "Post-capture control of a tumbling space debris via tether tension." *Acta Astronautica* 180 (2021): 317-327. https://doi.org/10.1016/j.actaastro.2020.12.049

[8] Hovell, Kirk, and Steve Ulrich. "Attitude stabilization of an uncooperative spacecraft in an orbital environment using visco-elastic tethers." *AIAA Guidance, Navigation, and Control Conference*. 2016. https://doi.org/10.2514/6.2016-0641

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Theoretical modeling and analysis of the launching process in an electromagnetic coil launcher

Cheng Yu[1], Meina Wang[1], Zongming Zhu[1], Maoying Zhou[1,*], Ban Wang[1,#], Juyong Zhang[1], Zhiping Chen[1]
1 School of Mechanical Engineering, Hangzhou Dianzi University, Hangzhou, China.
* Corresponding Author: myzhou@hdu.edu.cn
# Corresponding Author: wangban@hdu.edu.cn

Conference Topic: Space Tether Technology Development and Experimental Studies.

Along with the ever increasing human spatial activities, space debris which characterizes those nonfunctional, human-made objects staying in Earth orbit or re-entering into Earth's atmosphere have posed a great threat to other orbiting objects. As a result, tether-net based system has been extensively studied from various aspects due to their promising ability to capture space debris.

In general, the tether net capturing systems rely on a specific launching mechanism to shoot end masses attached to the net at a given velocity and orientation. The launching mechanisms thus require the release of the stored energy in a short time, which is later converted to the kinetic energy of the end masses. Conventionally, gunpowder, compressed gas, flywheel and controlled electric motor drive are used to achieve the short-time energy release. However, these methods are far from efficient with limited load and poor controllability. In comparison, electromagnetic launching based on electromagnetic forces can be a promising alternative, due to the high energy storage capacity, high launching frequency, fast start-up time, high system efficiency, strong continuous launch ability and strong load adjustability.

Electromagnetic launching, which have been extensively utilized in weapons, in general falls into three types: rail launchers based on moving rails on conducting guides, reconnection launchers based on projectiles moving over different planar coils, and coil launchers based on the motion of projectiles through cylindrical coils. Coil launchers will be our research object due to its simple structure and flexible designs. In fact, a coil launcher consists of a cylindrical coils, projectiles appropriate for the coil dimensions, and the power supplying systems for the coils, usually a charged super-capacitor. Upon triggered, the super-capacitor supplies electrical voltages to the coil, resulting in the current establishing in the coil. Hence, magnetic field builds up inside the coil. The ferromagnetic projectile is thus magnetized and subject to the action of magnetic pull. As a result, the projectile is launched.

The launching process as described above is extremely complex due to the involved electromagnetic interaction. Hence in this contribution, we are focused on the theoretical modeling and analysis of the launching process, especially the electromagnetic interactions involved. Starting from the classical Maxwell equations for electromagnetism, quasi-steady assumptions are made and the electromagnetic interaction is approximated by the magnetic potential descriptions. With domain decomposition method, the interested physical space are divided into several subregions according to their magnetic properties. Poisson equations are then established in different subregions with appropriate boundary conditions formulated. Continuity conditions are applied at the intersections between different subregions to guarantee a viable overall solution. Eigenfunction expansion methods are then utilized to solve the boundary value problem. The magnetic field in the system, the self-inductance of the whole system, and the magnetic forces experienced by the projectile are then analytically formulated. In the subsequent, dynamic equations of the projectile are set up considering the position dependent magnetic forces. Analytical and numerical results are thus given in terms of the exit velocities of the projectile and circuit properties. The results can be combined with the launching controlling circuits to allow for a better design of the whole launching system.

References

[1]Guan, Shaohua, et al. "Analysis of the influence of system parameters on launch performance of electromagnetic induction coil launcher." *Energies.* 2022, 15, (20), p. 7803.
[2]Diakov, P. A., A. A. Malashin, and N. N. Smirnov. "Dynamic processes in the tether of a space tethered system." *Acta Astronautica.* 2019, 163, pp. 100-106.
[3]Belguerras, Lamia, Smail Mezani, and Thierry Lubin. "Analytical modeling of an axial field magnetic coupler with cylindrical magnets." *IEEE Transactions on Magnetics*. 2021, 57, (2), pp. 1-5.
[4]Luo, Yao. "Field and inductance calculations for coaxial circular coils with magnetic cores of finite length and constant permeability." *IET Electric Power Applications.* 2017, 11, (7), pp. 1254-1264.
[5]Huang, Panfeng, et al. "A review of space tether in new applications." *Nonlinear Dynamics.* 2018, 94, pp. 1-19.
[6]Corwel, Christian, et al. "Design and control of an underwater launch system." *IEEE Access.* 2020, 8, pp. 38633-38649.
[7]Ma, Weiming, Junyong Lu, and Yingquan Liu. "Research progress of electromagnetic launch technology." *IEEE Transactions on Plasma Science*. 2019, 47, (5), pp. 2197-2205.
[8]Xie, Hong-bin, et al. "Research progress on advanced rail materials for electromagnetic railgun technology." *Defence Technology*. 2021, 17, (2), pp. 429-439.

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Suppression of Tether-net Shlinking Motion using Double-linked Bullet

H. Kojima[1], Y. Aoyama[2]
1 Tokyo Metropolitan University, Asahigaoka 6-6, Hino, Tokyo 191-0065, Japan, hkojima@tmu.ac.jp
2 Tokyo Metropolitan University, Asahigaoka 6-6, Hino, Tokyo 191-0065, Japan, aoyama-yamado@ed.tmu.ac.jp

Conference Topic: Tether Formation Flying, Space Net, and Enabled Missions

Space debris capture using a tether-net has attracted considerable research attention. In space, the tether-net starts to collapse owing to tension [1] because there is no aerodynamic drag to resist collapse. To prevent the collapse of the tether-net before debris capture (caused by tension after deployment), various approaches have been proposed, such as the addition of an adhesive material to the tether-net perimeter[2], or use of a thruster module attached to a weight that controls the weight trajectory after the ejection [3].

However, these mechanisms complicate the net design. To prevent the tether-net collapse prior to debris capture and to ensure its full deployment just before contact with the debris, a tether-net ejection mechanism with an adjustable ejection angle (Fig. 1) has been proposed, and comparisons between simulations and experiments demonstrated good agreement in the maximum deployment area, time to attain the maximum deployment, and the rebound and retraction speeds of the tether-net after complete deployment [4].

Although the tether-net ejection mechanism proposed in [4] is advantageous for adjusting the timing of tether-net full deployment, ejected tether-nets still have a tendency of reshrinking motion owing to the string tension after full deployment. Therefore, when target debris escapes from the debris removal satellite, the debris capture capability of the tether-net may deteriorate.

Figure 1. Ejection angle adjustment mechanismFigure Caption

To overcome this problem without installing a thruster module on the bullets, in this study, a double-linked bullet is proposed. This bullet consists of an inner weight and outer weight connected to the inner weight via a tether, as shown in Fig. 2, to suppress the rebounding motion of the bullet owing to the tension at the tether-net full deployment. It is expected that the outer weight flies outward and pulls the inner weight to cancel the impulsive tension at the tether-net full deployment. The idea behind this bullet design comes from the input-shaping technique, which is widely applied to suppression of vibrations.

In this study, the proposed double-linked bullet for suppressing the rebounding motion of the bullet is studied experimentally and its effectiveness will be demonstrated by comparing with the results obtained using a typical single bullet.

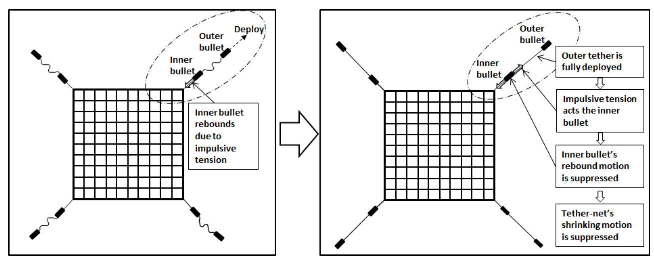

Figure 2. Double-linked bullet

References

[1] Chen, Q., Li, G., Zhang, Q., Tang, Q., Zhang, G., "Optimal design of passive control of space tethered-net capture system", IEEE Access, Vol. 7, 131383–1313942019,doi: 10.1109/ACCESS.2019.2939518.

[2] Zhang, G., Zhang, Q., Feng, Z., Chen, Q., and Yang, T. "A simplified model for fast analysis of the deployment dynamics of tethered-net in space". Adv. Sp. Res. Vol. 14, pp. 1960-1974, 2021, doi: 10.1016/j.asr.2021.04.032.

[3] Zhang, F., Huang, P. "Releasing dynamics and stability control of maneuverable tethered space net", IEEE/ASME Trans. Mechatronics, Vol. 22, No. 2, pp. 983-993, 2017, doi: 10.1109/TMECH.2016.2628052.

[4] Kato, Y., Kojima, H., Trivailo, P. M. "Performance evaluation of tether-net deployment with adjustable ejection angle", Advances in Space Research, Vol.73, No.5, pp. 2471-2487, 2024, doi: 10.1016/j.asr.2023.12.055.

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Cooperative Game Theory based Formation Control for Tethered Space Net Robot

Yifeng Ma[1,2], Fan Zhang[1,2], Yizhai Zhang[1,2], Panfeng Huang[1,2]
1 The Research Center for Intelligent Robotics, School of Astronautics, Northwestern Polytechnical University, Xi'an, Shaanxi China, yifengma@mail.nwpu.edu.cn
2 The National Key Laboratory of Aerospace Flight Dynamics, Xi'an, Shaanxi, China, fzhang@nwpu.edu.cn

Conference Topic: Tether Formation Flying, Space Net, and Enabled Missions

On-orbit services, such as debris removal and the capture of noncooperative targets, represent promising trends in future space development [1]. The Tethered Space Net Robot (TSNR) emerges as an innovative solution for active space debris capture and removal, as depicted in Figure 1. Its expansive envelope and straightforward capture method render it an appealing choice for such tasks. However, the challenges arise when capturing maneuverable debris with the flexible and elastic underactuated net. To prevent the risk of entanglement of flexible net and collisions among the Maneuverable Units (MUs), a minimal separation distance must be set. Simultaneously, a maximal separation distance is crucial to avoid the bouncing effect.

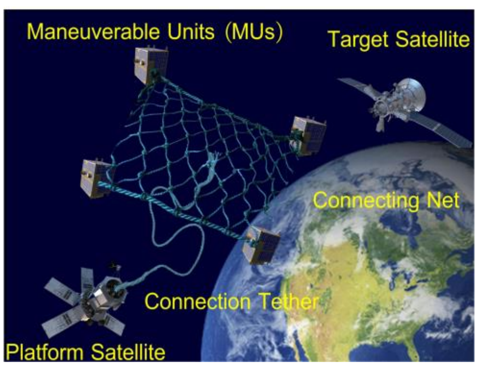

Figure 1. TSNR system

In recent years, researchers have extensively explored control challenges associated with the TSNR under relative constraints. For example, the study in [2] formulated formation-keeping control strategies, employing two artificial potential functions to preserve the TSNR's configuration while adhering to relative distance constraint. Additionally, [3] introduced a fuzzy-based adaptive super-twisting sliding mode control to estimate and suppress the complex oscillations of the TSNR.

However, prior studies solely concentrated on the overarching control objectives, neglecting the individual subjective initiative. Regarding the extra tension force caused by other MUs as mere perturbations can not completely reflect the dynamic interaction among the MUs.

Game theory serves as a fitting analytical method for addressing interaction formation issues of multi-agent systems. Lin [4] conceptualized the formation control problem of UAVs within the framework of differential game, suggesting an open-loop Nash strategy approach to achieve comprehensive distribution. Additionally, [5] explores a distributed game strategy for the formation control of multi-spacecraft, introducing a worst-case Nash strategy against the disturbance defined as a player.

Nonetheless, the current game-based methods designed for multi-agent systems are not applicable to the TSNR. The rigid formation constraints imposed by the flexible net mean any abrupt maneuver by a MU significantly impacts the system, introducing antagonism to the cooperative mission.

To address the aforementioned problems, a novel cooperative game based formation control scheme is proposed in this paper. Each Mu is dedicated to minimizing its own performance cost based on local information, while the system aims to attain an optimal strategy. The main contributions can be outlined as follows:

1. The cooperative game is established among the MUs in the TSNR, which makes up for the disadvantage that the traditional formation control methods only treat the interactions as disturbances that need to be compensated.

2. The game framework incorporates an energy estimate term. In the event of a formation change or abrupt maneuver by a MU, the extra energy consumption for stabilization is estimated in advance, prompting coordinated maneuvers by other MUs to mitigate it.

The enhancement in the task execution capability of the TSNR will be verified through a comparative analysis with traditional methods.

The proposed algorithm is generalizable, finding application not only in the TSNR but also in addressing formation control problems in other tethered systems.

References

[1] M. Shan, J. Guo, and E. Gill, “Review and comparison of active space debris capturing and removal methods,” *Prog. Aerosp. Sci.*, vol. 80, pp. 18–32, Jan. 2016, doi: 10.1016/j.paerosci.2015.11.001.

[2] Y. Liu, F. Zhang, and P. Huang, “Coordinated Control for Constrained Multiple Spacecraft System,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 56, no. 2, pp. 1189–1201, Apr. 2020, doi: 10.1109/TAES.2019.2926612.

[3] F. Zhang and P. Huang, “Fuzzy-Based Adaptive Super-Twisting Sliding-Mode Control for a Maneuverable Tethered Space Net Robot,” *IEEE Trans. Fuzzy Syst.*, vol. 29, no. 7, pp. 1739–1749, Jul. 2021, doi: 10.1109/TFUZZ.2020.2985325.

[4] W. Lin, “Distributed UAV formation control using differential game approach,” *Aerosp. Sci. Technol.*, vol. 35, pp. 54–62, May 2014, doi: 10.1016/j.ast.2014.02.004.

[5] J. Li, S. Chen, C. Li, and F. Wang, “Distributed Game Strategy for Formation Flying of Multiple Spacecraft With Disturbance Rejection,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 57, no. 1, pp. 119–128, Feb. 2021, doi: 10.1109/TAES.2020.3010593.

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Deployment and Descending Dynamics of a Large-scale Tether-Net for Asteroid Touchdown Missions

Jinyu Liu[1], Yu Zhang[2], Xingqun Zhan[3], Hexi Baoyin[2]
1.Global Institute of Future Technology, Shanghai Jiao Tong University, Shanghai, China, jinyu_liu@sjtu.edu.cn
2. School of Aerospace Engineering, Tsinghua University, Beijing, China,
yuzhang20@mails.tsinghua.edu.cn, baoyin@tsinghua.edu.cn
3. School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai, China, xqZhan@sjtu.edu.cn

Conference Topic: Planetary Exploration and Utilization

The key points behind the tether-net touchdown system is that many probes with initial releasing velocity connected by flexible tethers can land softly on asteroid under the influence of micro-gravitational force, which can be exploited to absorb or dissipate the kinetic energy as much as possible by tether damping without tumbling or bouncing. The mission scenario presented in this paper is the deployment of tether-net phase (see figure 1), the spacecraft is subjected to the gravitational pull of the asteroid and tether tension, whereas external space environmental perturbations are ignored. It is assumed that the size of the probe is small with respect to the large-scale of tether-net and asteroid. Thus, the probe equipped with thruster can be modeled as a point mass. At the same time, the model of the probe attitude also without consideration. The propulsion force generated from thruster gives the initial releasing velocity of net acting on its center of mass. Thereby, the motion trajectory of the flexible net in the asteroid's irregular gravity field be studied to give a solution for the key flexible attachment issues for the future's asteroid exploration missions.

(1) The application background of asteroid's exploration missions is introduced, and some problems and challenges that may be encountered is specified. Then the research methods of domestic and foreign scholars on orbit dynamics and the flexible net modeling in the asteroid's gravity field is reviewed. Finally, the strengths and weaknesses of different research methods presented is analyzed.

(2) The irregular gravity field of the asteroid is best fitted by the polyhedron method as well as the asteroid's parametric surface model is reconstructed by the spherical harmonic series method. On that basis, the orbital dynamics model is established to unify the dynamics research framework of the motion near and on the surface of the asteroid.

(3) A concentrated mass-spring and damping model is used to study the flexible net dynamics, and an adjacency matrix is applied for describing the topology of the flexible net, so that the internal force of each node is easily to be calculated. The collision dynamics of the flexible net is built up using the nonlinear spring-damping model. The condition of the collision is discussed. Then the expression of the normal contact force is presented based on the Hertz collision theory and Hunt-Crossley damping theory, and the tangential contact force is given by the coulomb friction law. Finally, the dynamics model of flexible net in the asteroid's gravity field is built up. Simultaneously, the detailed algorithm design flow for flexible net dynamics model is given.

(4) By solving the dynamic equations of the flexible net in parallel, the movement of the flexible net detector to land on the asteroid is simulated. Consequently, we give a metheod to solve the problems of the lander's rebound, escape and overturning in a weak field of gravitation.

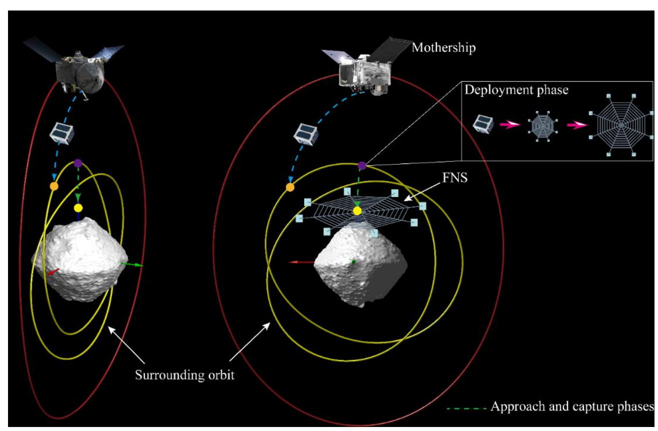

Figure 1. A large-scale tether-net for asteroid touchdown missions

THE SEVENTH INTERNATIONAL CONFERENCE ON TETHERS IN SPACE

(June 3rd, 2024)

ABSTRACT

Session 2 - Space Net & EDT

Chair: Prof. Hirohisa Kojima

- **Title:** Experimental Reconstruction of The Unfolding Process of The Electromagnetically Launched Flexible Tethered Net (2024076)
- **Title:** Tensile Experiment Based Self-Adaptive Dynamic Model for Tethered Space Net (2024066)
- **Title:** Numerical and Experimental Study on Effect of Net-Bullet Ejection Angles and Initial Distances on Successful Space Debris Capture (2024035)
- **Title:** Incentivizing Leo Debris Removal with Electrodynamic Tethers (2024081)
- **Title:** Optimal Spin-Up Control of Linear Tether Formation Using Electrodynamic Force (2024015)

Paper No: 2024076
7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Experimental reconstruction of the unfolding process of the electromagnetically launched flexible tethered net

Meina Wang[1], Zongming Zhu[1], Cheng Yu[1], Maoying Zhou[1,*], Ban Wang[1,#], Juyong Zhang[1], Zhiping Chen[1]
1 School of Mechanical Engineering, Hangzhou Dianzi University, Hangzhou, China.
* Corresponding Author: myzhou@hdu.edu.cn
# Corresponding Author: wangban@hdu.edu.cn

Conference Topic: Space Tether Technology Development and Experimental Studies.

With the continuous development and extensive application of space technologies, space debris has become an urgent problem due to its potential threat to working orbiters. To this end, various methods have been developed and investigated to capture and remove space debris, of which the tether-net capturing systems have emerged as a promising solution in recent years[1].

Typical tether-net capturing systems consist of a flexible net with several end masses attached, a storage cup with integrated launching mechanisms, and a long tether connected in between. When triggered upon receiving any control signals, the end masses are launched by the launching mechanisms at a given velocity and angle, which would then fly towards the target in space and pull the flexible net to unfold at the same time. As long as the flexible net comes into contact with the target, it wraps around the target and forms a net-target complex under the action of the tension in the tether. Dynamics of the flexible net[2], including its deployment from storage[3], flight in space, contact with the target[4], and closure after capture[5], have thus attracted tremendous research attention in the past decades. Various launching mechanisms are put forward and tested to allow for a reliable net launching process[6]. Different types of approximations for the net structure are put forward and utilized with numerical simulations conducted to elucidate the flight dynamics of the net[7].

Yet few experimental efforts have been made successfully to reconstruct the net unfolding process after launching. Several aspects are to be blamed for the absent experimental results[8]. Firstly, the flexibility and light weight of the net make it difficult to simultaneously capture all necessary coordinate information from experiments. Secondly, the net overlaps itself in the unfolding process and thus makes it harder to extract the exact shape. Thirdly, viewed as a spatial curved surface, it is not so clear how to recover the net shape from experimental observations efficiently.

Here in this paper, we are focused on the experimental reconstruction of net shape in the unfolding process. Optical markers are added to the flexible net in the hope that the unfolding process is not much affected while the optical markers can be readily recognized by conventional image processing algorithms. Multiple high frame rate cameras are set up to simultaneously capture the unfolding net in the experiments. With enough captured images, spatial coordinates of different optical markers on the net are then determined with a specifically designed algorithm. After that, spatial shapes of the net at different time instants in the unfolding process are reconstructed. In this sense, the whole unfolding process of the flexible net is characterized, which can be extremely useful in the design and optimization of the whole space tether-net capturing systems.

References

[1] S. Chen, C.T. Woods, A. Boonrath, E.M. Botta, Analysis of the robustness and safety of net-based debris capture, in: AIAA SCITECH 2022 Forum, 2022, pp. 1001.
[2] W. Huang, D. He, Y. Li, D. Zhang, H. Zou, H. Liu, W. Yang, L. Qin, Q. Fei, Nonlinear dynamic modeling of a tether-net system for space debris capture, Nonlinear Dynamics, 110 (2022) 2297-2315.
[3] H. Sakamoto, M.R. Mughal, A. Slavinskis, J. Praks, P. Toivanen, P. Janhunen, M. Palmroth, E. Kilpua, R. Vainio, Verification of tether deployment system aboard CubeSat through dynamics simulations and tests, in: 2021 IEEE Aerospace Conference (50100), IEEE, 2021, pp. 1-7.
[4] S. Li, Y. She, Recent advances in contact dynamics and post-capture control for combined spacecraft, Progress in Aerospace Sciences, 120 (2021) 100678.
[5] Y. Zhao, F. Zhang, P. Huang, Dynamic Closing Point Determination for Space Debris Capturing via Tethered Space Net Robot, IEEE Transactions on Aerospace and Electronic Systems, 58 (2022) 4251-4260.
[6] M. Ru, Y. Zhan, B. Cheng, Y. Zhang, Capture Dynamics and Control of a Flexible Net for Space Debris Removal. Aerospace 2022, 9, 299, in, s Note: MDPI stays neu-tral with regard to jurisdictional claims in …, 2022.
[7] M. Zhen, L. Yang, Y. Zhu, H. Huang, J. Hu, The Impact Dynamics and Simulations of Space Net, in: International Conference on Guidance, Navigation and Control, Springer, 2022, pp. 1486-1498.
[8] A. Boonrath, E.M. Botta, Validation of Models for Net Deployment and Capture Simulation with Experimental Data, Journal of spacecraft and rockets, (2023) 1-19.

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7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Tensile experiment based self-adaptive dynamic model for tethered space net

Weiliang Zhu[1,2], Zhaojun Pang[1], Ju He[1], Jia Guo[1], Wei Zhao[1], Zhonghua Du[1], Zheng H. Zhu[2]
1 School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, China, bywzwl@163.com
2 Department of Mechanical Engineering, York University, Toronto, Canada, gzhu@yorku.ca

Conference Topic: Fundamental Research on Space Tethers

Tethered Space Net is a common method for mitigating the space debris crisis, with their dynamics widely studied using mass-spring-damper models. However, this linearized dynamic model struggles to accurately represent the nonlinear dynamic characteristics of tethers and nets when subjected to significant tensile deformation. Current dynamic modelling methods typically use the elastic modulus of fibres to directly construct the dynamic models of braided tethers or nets, which may overly simplified and fail to describe the nonlinear nature. In this study, quasi-static tensile tests are conducted on eight-strand braided Dyneema tethers with diameters of 0.4 mm, 0.47 mm, 0.63 mm, 0.8 mm, and 1.0 mm. The tensile mechanical curves of the tethers were observed, and the prevalent nonlinearity in the tensile process and its mechanisms are analysed.

The results indicate that the elastic modulus of braided tethers is time-variant during the tensile process, increasing with tension. This nonlinearity is more pronounced in thicker tethers. The specific braiding method creates gaps and interweaving among fibres, which initially relieves the stretching of the fibre, resulting in macroscopic deformation significantly greater than the actual fibre strain. Consequently, the elastic modulus of the tether is measured average elastic modulus ranging between 10GPa and 12GPa, which is much lower than that of the Dyneema fibres 87GPa to 110GPa. The measured failure stress of the tethers ranges from 1.35GPa to 1.65GPa (with Dyneema fibre strength between 3.3GPa and 3.9GPa [1]). And the failure strain ranges from 0.12 to 0.16, which is lower than the fibres.

To accurately characterize the nonlinear tension of tethers, we propose a self-adaptive spring-damper model based on tensile experiments for accurately characterizing the nonlinear mechanical properties of tethered space nets. This model adjusts the element stiffness adaptively during the tensile process, resulting in a nonlinear unit model that closely matches the actual behaviour of the tether units. Our approach provides a more accurate dynamic model for space nets and tethers, enhancing their effectiveness in mitigating space debris. This work will provide a valuable reference for the modelling of space tethers and space nets.

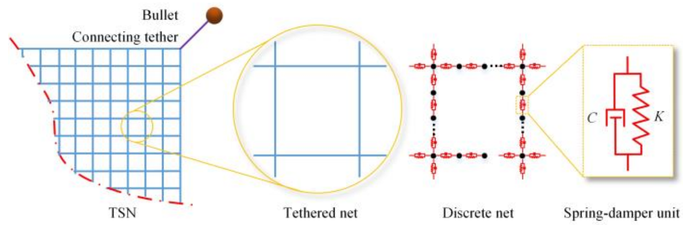

Figure 1. Dynamic modelling of the net

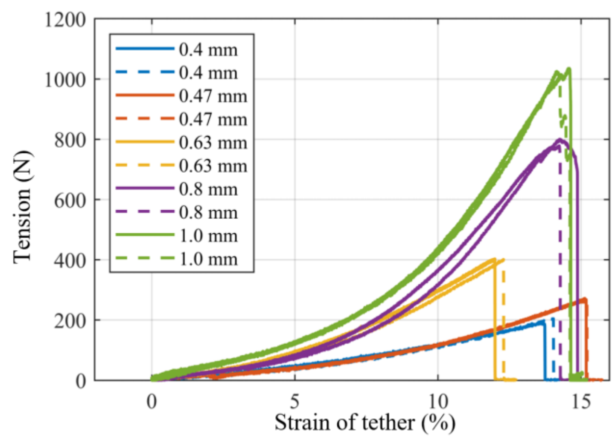

Figure 2. Nonlinear behavior of tether unit in quasi-static tensile experiment

References

[1] B. Sanborn, A.M. DiLeonardi, T. Weerasooriya, Tensile Properties of Dyneema SK76 Single Fibers at Multiple Loading Rates Using a Direct Gripping Method, J. Dynamic Behavior Mater. 1 (2015) 4–14. https://doi.org/10.1007/s40870-014-0001-3.

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7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Numerical and Experimental Study on Effect of Net-bullet Ejection Angles and Initial Distances on Successful Space Debris Capture

A.R. Pandie[1], H. Kojima[1]
[1]Tokyo Metropolitan University, Tokyo, Japan, 191-0065, pandie-andry@ed.tmu.ac.jp, hkojima@tmu.ac.jp

Conference Topic: Tether Formation Flying, Space Net, and Enabled Missions

The escalating presence of space debris poses a dual threat to active spacecraft, both in terms of cost and safety. Recognizing this hazard, there is a growing emphasis on the active removal of space debris [1]. One prominent technique gaining attention is the use of nets, which involves deploying, contacting, and wrapping around debris.

The assessment of the initial distance between target debris and the net ejector emerges as a pivotal variable influencing the efficacy of space debris capture. This distance is expressed as a ratio to the one-sided length of the net, assuming it ranges from 100% to 300%. A comprehensive methodology is adopted, integrating numerical simulations and practical experiments to identify optimal parameters for successful space debris capture using the net technique [2]. The tether net dynamic features, encompassing maximum area, deployment time, flight distance, and effective period, define the parameters for a space debris removal mission [3]. These aspects are contingent on initial shooting parameters like speed, ejection angle, bullet mass, and net material.

Numerical simulations, executed using Python Spyder and Blender, cover a diverse array of active debris removal scenarios. Meanwhile, practical experiments employ a carefully calibrated spring-based net launch system with corner masses, capturing data through high-speed cameras. The material chosen for the net, Kevlar, is justified through its lightweight, durable, and flexible properties, confirmed by numerical simulations.

To enhance realism, 3D-printed mockup debris, crafted from a plastic polymer, is used in testing. Acknowledging the challenge of replicating space conditions on Earth, experiments assume an artificial zero gravity setting, with meticulously determined initial conditions. The net's trajectory, factoring in air resistance, shooting speed, and contact dynamics with debris, is rigorously determined through equations of motion. The contact is assumed to occur at the debris's peak height and zero speed.

The expected outcome of this study is to test the factors that impact the probability of the net to capture mockup debris, including initial velocities, relative distances, and shooting direction.

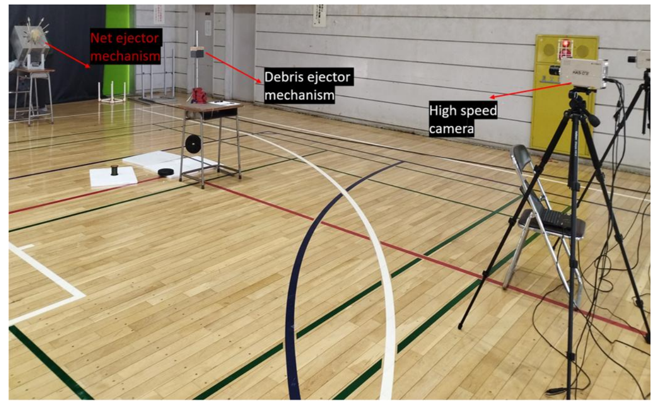

Figure 1. The setup of the experiment

Table 1. System parameters

Parameters	Values
Net dimension (L_{net})	1 m
Drag coefficient of net	0.36
Amount of bullets	4
Total mass of bullet	92 g
Bullet ejection angle	15, 30, 45°
Shooting speed of bullet	7.7 m/s
The height of net from the ground	129.4 m
Debris mass	150 g
Drag coefficient of debris	0.8
Debris dimension	10 cm
Motion of debris ejection	Vertical upward

References

[1] Forshaw, J. L., et al. "RemoveDEBRIS: An in-orbit active debris removal demonstration mission", Acta Astronautica, Vol. 127, pp. 448-463, 2016, doi: 10.1016/j.actaastro.2016.06.018.

[2] Medina, A., et al. "Validation results of satellite mock-up capturing experiment using nets", Acta Astronautica, Vol. 134, pp. 314-332, 2017, doi: 10.1016/j.actaastro.2017.02.019.

[3] Shan, M., Guo, J., Gill, E. "Deployment dynamics of tethered-net for space debris removal", Acta Astronautica, Vol. 132, pp. 293-302, 2017, doi: 10.1016/j.actaastro.2017.01.001.

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7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Incentivizing LEO Debris Removal with Electrodynamic Tethers

Ritu Bhalodia[1], Jesse K. McTernan[1], and Sven G. Bilén[1]
[1]The Pennsylvania State University, University Park, PA, USA, sbilen@psu.edu

Conference Topic: Tether Power Generation and Energy Harvesting; Tether-based Systems for Space Debris Remediation

As the cost of access to space continues to decrease, the quantity of space objects and debris will increase significantly. This growth in space debris is of huge concern to the reliable operation of space assets; hence, mitigation of debris generation as well as removal of existing debris is of growing importance. In particular, large objects, such as the upper stages of launch vehicles and defunct satellites, pose a significant threat of populating low Earth orbit (LEO) with a substantial quantity of debris. After achieving the desired orbit, upper stages are left with too little propellant to deorbit themselves, increasing the probability of collisions and potential explosions due the residual propellant. The possibilities only increase as LEO becomes more populated with debris.

Typically considered only as objects to be removed from orbit, space debris have value in their potential and kinetic energy, which depends on their mass and orbital properties. This "embodied" energy [1] represents an opportunity for spacecraft in LEO equipped with an electrodynamic tether (EDT) to simultaneously deorbit space debris while converting the orbital energy of the debris into useful electrical energy. As this occurs, the spacecraft–debris system loses altitude, and ultimately deorbits. However, the EDT spacecraft need not fully deorbit as the debris can be released in a lower orbit to decay out. Then, the same process that decreased altitude can be used in reverse to boost the EDT spacecraft's orbit and to recharge its "orbital battery" through the use of energy sources such as solar panels.

Although there are over 36,500 pieces of debris exceeding 10 cm in diameter in LEO as of 2023 [2], this study focuses on 50 derelict objects that are identified as particularly concerning. Using the Linux-based simulation software, TeMPEST [3], we simulate an EDT system with an energy storage module for the deorbiting of these objects. By systematically varying EDT properties and orbital elements, the simulation aims to ascertain the optimal operational range for the EDT system. We discuss some of the system considerations and some the economic offsets afforded by EDTs for debris mitigation. Using EDTs could incentivize the targeting of large debris objects that contain the largest amounts of embodied energy and are also the largest debris-creation hazards.

For example, spacecraft in LEO often include multiple instruments for scientific research, which puts large demands on the power system. Typically, solar arrays and batteries supply power and can represent a large portion of the spacecraft's overall mass, volume, and surface area—thus increasing launch and manufacturing costs. A relatively low-mass EDT can replace a significant portion of the power system, particularly for high-power needs. Such EDT systems can generate kilowatts of power, far greater than is feasible via other means, particularly on small-scale spacecraft. Employing such a system, a small spacecraft has the ability to enable scientific opportunities and reduce costs by repurposing the embodied orbital energy of debris to perform high-power missions, instead of scaling up its power systems by increasing the size of solar panels or energy storage devices on board. The reduction in mass due to the use of EDT systems could yield significant reductions in launch and mission costs with the added benefits of debris removal and exploiting new opportunities for small-scale spacecraft.

References

[1] McTernan, J.K. and S.G. Bilén, "Embodied energy repurposing via energy-harvesting electrodynamic tethers," *Journal of Spacecraft and Rockets*, Vol. 54, No. 4, 2017.

[2] ESA, "Space Environment Statistics," online: https://sdup.esoc.esa.int/discosweb/statistics/, accessed Jan. 2024.

[3] Borderes-Motta, G., et al. "Cross-verification and benchmarking analysis of electrodynamic tether simulators," *Acta Astronautica*, Vol. 208, Pages 381–388, 2023.

Optimal Spin-up Control of Linear Tether Formation using Electrodynamic Force

H. Lu[1], C. Wang[1], Y. M. Zabolotnov[2], A. Li[1]

1 School of Automation, Northwestern Polytechnical University, Xi'an, China, luhs@nwpu.edu.cn
2 Samara National Research University, Samara, Russia

Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

Spinning linear electrodynamic tether formation (SLETF) consists of three linearly distributed nano-satellites connected by two conductive tethers, which combines the advantages tether formation, electrodynamic tether and spinning tether: multiple tethers provide better mission flexibility, electrodynamic force provides a propellant-free thrust, and its spinning motion around the system mass center provides good centrifugal stability at the tips of both tethers [1]. Therefore, SLETF is considered to be promising in constructing observation platforms, artificial gravity, space station, and so on. Among all operation stages, the spin-up process is a preliminary stage for all spinning tether systems, and its main challenge is that tethers are unstable during such a transition process. In the vulnerable spin-up process tethers may become slack or even entangled with tethered satellites due to significant tether deformation, and the spin-up process of a SEDTF is even more complicated than that of a single-tether system due to the coupling effect of two tethers. Current research mostly studies the deformation control of a single tether system[2], or the spin-up control of a SLETF neglecting tether flexibility [3], therefore, it is still an unresolved problem to design a synchronized spin-up control strategy considering flexible tether motion.

To deal with this problem, this paper mainly studies the spin-up control of a SLETF by considering tether flexibility. First, two models are used: The Lagrangian model is used for controller design and the flexible lumped model is used for analyzing flexible tether motions. Then, uncontrolled tether deformations are examined under the open-loop on/off program. Fig. 1 indicates that tethers become significantly deformed and spin unsynchronically under the open-loop program, the equivalent length of which decreases to 90.5% of linear tether length. Third, to stabilize significant tether deformations, an optimal controller based on Bellman dynamic programming is proposed for the spin-up process. The objective function of the optimal controller is set to stabilize tether deformation and ensure tracking spinning rate at the same time. Fig.2 shows that, under the regulation of the proposed optimal controller, tether deformations are reduced to an insignificant level (96.5% of linear tether length), and tethers spin synchronically around the designated spinning rate.

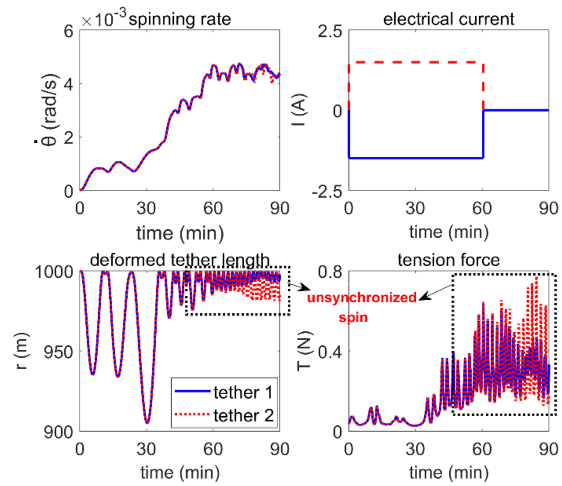

Figure 1. System motion with open-loop program

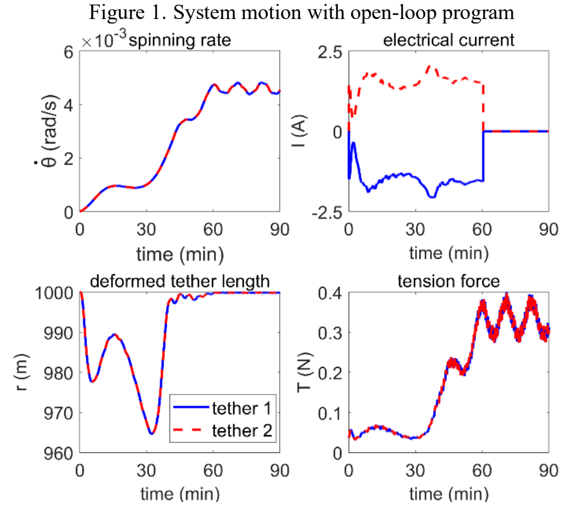

Figure 2. System motion with optimal controller

References

[1] Yu, B. S., Ji, K., Wei, Z., Jin D. "In-plane global dynamics and ground experiment of a linear tethered formation with three satellites," Nonlinear Dynamics, Vol. 108, No. 4, pp. 3247-3278, 2022.
[2] Lu, H., Li, A., Wang, C., Zabolotnov Yu. M. "Tether Deformation of Spinning Electrodynamic Tether System and Its Suppression with Optimal Controller", Journal of Aerospace Engineering, Vol. 34, No. 2, pp. 04021003, 2021.
[3] Luo, C., Huang, L., Wen, H., Kang, J., and Jin, D. "Model predictive control for spin-up maneuver of an electrodynamic tether system," Acta Astronautica, Vol. 189, pp. 55-62, 2021.

THE SEVENTH INTERNATIONAL CONFERENCE ON TETHERS IN SPACE

(June 3rd, 2024)

ABSTRACT

Session 3 – EDT & Space Elevator

Chair: Prof. Sven Bilen

- **Title:** Orbital States Keeping of the Floating Partial Space Elevator Using Reinforming Learning Method (2024005)
- **Title:** Electrodynamic Tether and Brake Sails Combination Deorbit Design (2024006)
- **Title:** Modeling and Mode-Shape Analysis of Electrodynamic Space Tethers Using Geometric Computational Dynamics (2024085)
- **Title:** A Review of Electrodynamic Tether Missions from a Dimensionless Analysis Perspective and to Promote the Opening and Support of Markets in the Space Sector (2024041)
- **Title:** EDT Demonstration for Keeping Low Altitude Orbit Using Carbon Nanotube Tether (2024082)

Paper No: 2024005
7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Orbital States Keeping of the Floating Partial Space Elevator Using Reinforming Learning Method

Gefei Shi*[1, 2, 3], Xuerong Yang[1, 2]
1. School of Aeronautics and Astronautics, Sun Yat-sen University, Guangzhou 510275, P.R. China, shigf@mail.sysu.edu.cn
2. Shenzhen Campus of Sun Yat-sen University, Shenzhen, Guangdong 518107, P. R. China
3. Shenzhen Key Laboratory of Intelligent Microsatellite Constellation, Shenzhen 518107, P. R. China

Conference Topic: Fundamental Research on Space Tethers, Space Elevator.

The partial space elevator (PSE) is a promising technology in the low-cost cargo transportation for the space station and the future's on-orbit assembly of ultralarge space constructions. A PSE generally consists of one main satellite, one end body, and a climber moving along the tether between them. In the cargo transfer mission, the climber's movement leads to obvious orbital radius changing of the main satellite which is adverse to its stability and safety. Thus, it is critical to keep or adjust the orbit states of the main satellite within a desired range.

Up to date, several methods have been proposed to keep the main satellite's orbital states by optimizing the climber speeds [1, 2] or mission planning [3]. The previous method [1, 2] controls the main satellite's orbit states directly in one transfer mission implemented by tensions in tether and thrusters on the main satellites, climber, and end body. The mission-based method [3] aims to reduces the changing magnitude of the main satellite's states by selecting the waiting period between the upward and downward transfer missions. Yet considering the dynamic coupling and nonlinear of the PSE, it is difficult to choose a reasonable length of the waiting period between upward and downward missions.

This work aims to give a new mission-based method to solve the aforementioned problem, preliminarily. First, a six-degree-of-freedom two-piece dumbbell model has been built. Then, a new mission planning strategy is proposed using the reinforcement learning (RL) method trained by the deep Q-network algorithm in which the waiting time is regarded as the action of the agent. A new reward function has been designed to estimate the main satellite's stability after cargo transportation. As shown in Fig. 1, the waiting time generated by the new RL method makes the orbital radius changing magnitude after the mission reduce over 88% comparing to the case in which the waiting time is one orbital period, see the blue lines in (a) and (b). The simulation results validate the proposed mission-based method.

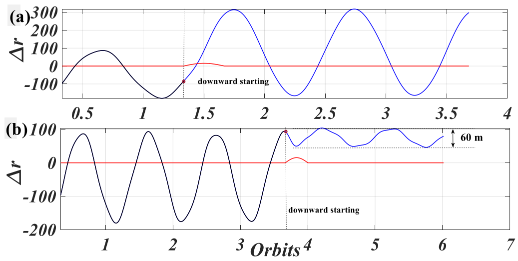

Fig. 1 Results: (a) waiting one orbit period (without planning). (b) RL method.

References

[1] Gefei Shi, and Zheng H. Zhu. "Orbital radius keeping of floating partial space elevator in cargo transposition", Astrodynamics, Vol. 7, pp. 259 – 269, 2023, doi: 10.1007/s42064-022-0156-y.
[2] Gefei Shi, and Zheng H. Zhu. "Libration-free cargo transfer of floating space elevator", Nonlinear Dyn, Vol. 110, pp. 2263 – 2281, 2022, doi: 10.1007/s11071-022-07729-4.
[3] Gefei Shi. "A Mission-based Orbit Keeping Method of the Partial Space Elevator", AIAA ASCEND 2021, November 15-17, 2021, Las Vegas, Nevada & Virtual.

Paper No: 2024006
7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Electrodynamic Tether and Brake Sails Combination Deorbit Design

H.Jiang[1], R. Zhong[2], R. Qi[3]
1Beihang University, Beijing, China, jiangheng@buaa,edu.cn
2Beihang University, Beijing, China, zhongruia@163.com
3Beijing Institute of Technology, Beijing, China, qirui@bit.edu.cn

Conference Topic: Tether-based Systems for Space Debris Remediation

Given the growing threat of an impending space debris crisis, nations worldwide have intensified their research efforts in satellite deorbiting technologies. Electrodynamic tether and braking sails stand out as popular methods for spacecraft deorbiting that do away with the necessity for propellant. However, these methods possess their own set of limitations. This paper presents a holistic dynamical model for a fusion of electrodynamic tether and braking sails. The aim is to address the complex nonlinear dynamics during the deployment, retrieval, and dwell time of electrodynamic tether, while compensating for the insufficient trust generated by braking sails in high orbital environments. The objective is to enable satellite to deorbit swiftly and stably under a broader range of conditions. Specifically accomplishing the following three aspects: conceptualizing the design of an ideal equipment, implementing simulated deorbiting process, and conducting an efficiency comparative analysis with prevalent current deorbiting methods. Through numerical simulations, the effectiveness and feasibility of this proposed design have been validated.

Table 1. Simulation parameters

Parameters	Values
Total mass	500kg
Eccentricity	0
Angle of orbit perigee	0°
Orbit Incline	0°
Braking Sail Area	10m²
The length of the tether	4.4m
The number of strands in the tether	10、20、30

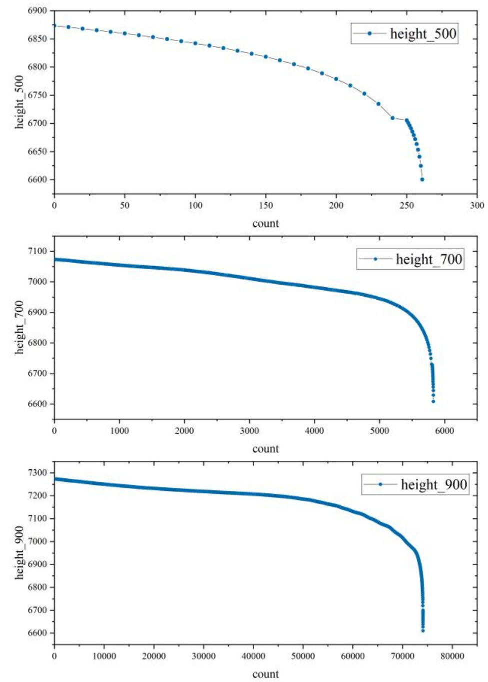

Figure 1. Comparison of Orbital Altitude Reduction

References

[1] Zuo, X., et al. (2023). "Station-keeping strategy for tethered drag sail-based transverse formation." Advances in Space Research 72(4): 1038-1051.

[2] Valmorbida, A., et al. (2022). "Validation of enabling technologies for deorbiting devices based on electrodynamic tethers." Acta Astronautica 198: 707-719.

Paper No: 2024085
7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Modeling and mode-shape analysis of electrodynamic space tethers using geometric computational dynamics

M. Kakavand[1], Z. H. Zhu[2]
1 Lassonde School of Engineering, Toronto, Canada, manivand@yorku.ca
2 Lassonde School of Engineering, Toronto, Canada, gzhu@yorku.ca

Conference Topic Fundamental Research on Space Tethers Mathematical Modeling of Space Tethers, Dynamics, Controls

Electrodynamic space tethers, a promising technology for various space applications, rely on the interaction between the tether and the Earth's magnetic field to generate thrust or induce orbital changes without the need for traditional propellants. This innovative approach offers potential benefits such as enhanced maneuverability, reduced mission costs, and increased mission longevity.

Our study addresses the development of a Lie group variational integrator for high-precision simulations of electrodynamic space tethers, along with the application of geometric Jacobian theory to analyze the system's mode shapes. The dynamics consists of two spacecraft connected by a discretized, elastic tether, and a tether reeling mechanism that adjusts the length of the tether. Fig. 1 illustrates a schematic of the components of the dynamic model.

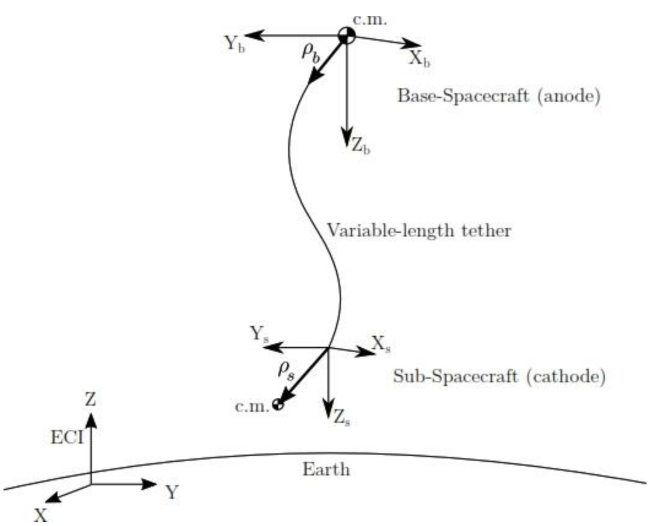

Figure 1. Schematic of the electrodynamic model

By employing the discrete-time analogue of the Lagrange-d'Alembert principle, we derive the discrete-time Euler-Lagrange equations governing the dynamics of the electrodynamic space tether. The resulting discrete-time dynamic model, in a compact form, naturally evolves on a Lie group, preserving the configuration manifold structure without constraints. The use of Lie Group methods also avoids the singularities encountered in representation of the attitude dynamics of rigid bodies using the conventional Euler angles or the ambiguity of employing quaternions. As a result of employing the discretized Lagrange d'Alembert principle, the integrator exhibits excellent energy preservation, suitable for long-time simulations and the simulation of aggressive maneuvers. Such desirable properties ensue from the fact that the developed numerical algorithm describes a discrete dynamical system that approximates the flow of the differential equation rather than solely focusing on numerically approximating a single solution trajectory, which is the case in conventional numerical algorithms such as Runge-Kutta methods.

To incorporate the electrodynamics, we make several assumptions: the base-spacecraft serves as the anode, the sub-spacecraft as the cathode with a cathode contactor, resulting in a positively biased tether; a bare tether is used; the electrical circuit is passive; ohmic loss potential drop is negligible, and the ions collected are significantly fewer than electrons. External forces acting on the system include control torque on the tether reeling drum, Lorentz force on the tether, and aerodynamic force on both spacecraft and the tether. We employ variational-based linearization to linearize the system and determine its geometric Jacobian, facilitating the identification of vibrational mode shapes that include the coupling between the tether and the two spacecraft.

Finally, simulation results for an electrodynamic space tether system in Earth's orbit are presented for three different cases. The first simulation aims to demonstrate the efficiency and accuracy of the developed numerical algorithm, in which the dynamics of the system without considering the external forces are studied. It is shown that the variational integrator has excellent energy preservation properties. The second and third simulation scenarios include the demonstration of the performance of a simple tether length controller and the use of the Lorentz force for the purpose of deorbiting the system.

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7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

A Review of Electrodynamic Tether Missions from a Dimensionless Analysis Perspective and as a Lever to Open and Boost Markets in the Space Sector

G. Sanchez-Arriaga[1], E.C. Lorenzini[2], and S. G. Bilén[3]
[1]Universidad Carlos III de Madrid, Aerospace Department, Madrid, Spain, Gonzalo.sanchez@uc3m.es
[3]University of Padova, Dept. of Industrial Engineering, Padova, Italy, enrico.lorenzini@unipd.it
[3]The Pennsylvania State University, School of Engineering Design and Innovation, University Park, PA, USA, sbilen@psu.edu

Conference Topic: Lessons Learned from Past Missions

More than fifteen experiments with electrodynamic tethers (EDTs) have been flown to date. These mission have provided valuable information on tether dynamics, electrical contact with the ambient plasma, thrust and drag generation, and wave emission, among others (see Refs. [1] and [2] and references therein). They also covered a wide range of orbital conditions (motional electric field and plasma density), tether lengths and cross-sections (wires and tapes), and system architectures to make electrical contact with the ambient plasma, including insulated EDTs with active plasma contactor at both ends, insulated EDTs with passive anodic contact and an active cathodic contactor, bare EDTs with an active cathodic contactor, and floating bare EDTs. Hollow cathodes, thermionic emitters, and field emission cathodes have been used as active cathodic contactors. Consequently, past EDT missions have covered a wide spectrum in the space spanned by the characteristics dimension-less parameters [3] that govern their physical principles of operation. The objective of this work is organizing past EDT missions and projects according to these parameters with the aim of steering future EDT research and missions and foster the use of EDTs as a lever to open new markets in the space sector.

The study first collects basic data from previous EDT missions, like tether dimensions and geometry and current levels, as well as environmental variables like plasma density and temperature, magnetic field, and motional electric field. Some EDT missions that did not fly, like ProSEDS [4], and missions that are expected to fly soon, like E.T.PACK [5], are also considered. In addition, for missions with insulated EDTs, synthetic data in the hypothetical case of substituting the insulated EDT by a bare EDT were generated.

The collected data were then used to compute the most important dimensionsless parameters related to tether–plasma anodic and cathodic contact, the current–voltage profiles along the EDT, dynamics, and performance. The dimensionless parameters were used to organize past EDT missions into different categories attending to the current collection regime, importance of ohmic effects, severity of the dynamic conditions, and wave excitation, among others. The missions are presented in figures with the axes being the dimensionless parameters, thus easing the identification of regions that are well populated by past EDT missions and void regions where it would be desirable to prepare future EDT missions.

The outcome of the analysis, together with key capabilities already demonstrated by past EDT missions, suggests that EDTs can be used as a lever to open and boost markets in the space sector. For instance, beyond the development of a tougher regulation, finding incentives for implementing post-mission disposal has been historically difficult due to the added mass and cost of the deorbit device. Similarly, the market of in-orbit-servicing, which is expected to generate about US$4 billion in the 2023–2032 period [6], would benefit extraordinarily from a propellantless orbital manoeuvring vehicle. With the aim to provide ideas for addressing these needs of the space sector, the work includes a discussion on using EDTs to generate added value in deorbiting and in-orbit servicing scenarios. Some of them are based on collecting useful scientific information [7] and energy repurposing [8] as a byproduct, thus opening the possibility of attracting new players that could finance the deorbit device. An example is exciting plasma waves, a task that have been already demonstrated by past EDT missions [9] and it is of interest for geophysicists. Similarly, the simultaneous deorbiting of space debris by several EDTs opens the possibility of making *in-situ* multi-point measurements of the ionosphere and studying large scale phenomena. The discussion also considers the dual use of EDTs in microlaunchers for both deorbiting at the end of life and raise the orbit altitude before the payload are release. The latter can save propellant mass and lower the insurance cost because the EDTs could also work as a backup propulsion system.

References

[1] Levin, E. M., Dynamic analysis of space tether mission, Advances in the Astronautical Sciences, 126, 2007.

[2] Aslanov, V. and Ledkov, A.S., Survey of tether system technology for space debris removal missions, Journal of Spacecraft and Rockets, 60(3), 1–81, 2023.

[3] Sanmartin, J., Lorenzini, E.C., and Martinez Sánchez, M., Electrodynamic tether applications and constraints, Journal of Spacecraft and Rockets, 47 (3), 2010.

[4] Johnson, C. L., Johnson, L., Gilchrist, B., Lorenzini, E., Stone, N., and Wright, K., Propulsive Small Expendable Deployer System (ProSEDS) Experiment: Mission overview & status, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit 20–23 July, Huntsville, Alabama 2003.

[5] Sánchez-Arriaga, G., Naghdi, S, Wätzig, K., Schilm, J., Lorenzini, E. C., Tajmar, M., Urgoiti, E., Tarabini Castellani, L., Plaza, J. F., and Post, A., The ETPACK project: Towards a fully passive and consumable-less deorbit kit based on low-work-function tether technology, Acta Astronautica 177, 821–827, 2020

[6] Eurconsult, Space Logistic Markets 2023, April, 2023.

[7] Sanmartin, J., A review of electrodynamic tethers for science applications, Plasma Sources Science and Technology, 19, 034022, 2010.

[8] McTernan, J. K. and Bilén, S. G., Embodied energy repurposing via energy-harvesting electrodynamic tethers, Journal of Spacecraft and Rockets, 2017, DOI: 10.2514/1.A33783.

[9] Wilson, T. L., Chlouber, D., and Jost, J., Electrodynamic tether currents in the day/night ionosphere: Correlations during the Plasma Motor Generator mission, J. of Geophysical Research, 101 (A10), 21,657–21,688, 1996.

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EDT Demonstration for Keeping Low Altitude Orbit Using Carbon Nanotube Tether

M. Nohmi[1], K. Matsuo[1], S. Kawamoto[2], Y. Ohkawa[2]
1Shizuoka University, Hamamatsu, Japan, nomi.masahiro@shizuoka.ac.jp
2 JAXA, Tokyo, Japan

Although there are many satellites in orbit around the Earth, relatively few have satellites at altitudes below 400km, but their orbital lives are short. Therefore, here proposes to extend their orbital lives using the conductive tether by electric propulsion and expand the use of space at ultra-low altitudes. At low altitudes, atmospheric resistance accelerates the descent into lower orbit, so electric propulsion is needed to overcome this. In particular, the tether is lightweight and has a large extension area, so it has a large atmospheric resistance, so it is used advantageously when descending into lower orbit to prevent debris generation, but it is necessary to reduce atmospheric resistance when ascending into higher orbit in our proposal. Also, compared to orbit descent, orbit ascend requires a lot of electrical energy.

This project is planning to demonstrate a system that overcomes atmospheric resistance and maintains its orbit using Electrodynamic Tether (EDT) using a micro-satellite. The mission details are as follows. The conductive tether is extended and stabilized in the earth direction by the gravity gradient. By emitting electrons from an electron emitter mounted on a high-altitude satellite and collecting electrons around a low-altitude satellite, a current is generated from the high-altitude side to the low-altitude side. According to Fleming's law, the Lorentz force is generated in the direction of the orbit and accelerates, so it can be propelled in the upward direction of the orbit. Atmospheric resistance, conductive tether propulsion, etc. change greatly due to the influence of solar activity, but it is estimated that it is possible to maintain the orbit with a current of about 50 mA. This project also aims to improve electrical performance and reduce the area of atmospheric resistance using a tether made from carbon nanotubes (CNT), a proprietary technology (manufacturing string-like CNT is considered difficult). The tether is insulated from space plasma by a coating on the high-altitude side and collects electrons as a bare tether on the low-altitude side. They will also use an improved electron-emitting device using carbon nanotubes, which is being developed at JAXA.

This paper describes the conceptual design of the micro-satellite whose mission is to maintain orbit using Electrodynamic Tether.

First, simulation analysis for Electrodynamic Tether mission has been described. The orbital environment, such as atmospheric resistance and plasma density, will be modeled, the tether will be expressed using a discretized model, and dynamics simulations will be performed. Electron emitting experiments were performed on an electron-emitting device using improved carbon nanotubes and incorporate the results into simulations. There are two main purposes for simulation evaluation in satellite design. First, when ascending the orbit using ElectroDynamic, it is necessary to raise the tether potential, and it is necessary to provide efficient power supply. The second step is to evaluate the ratio of the covered part to the bare tether that enables efficient potential-controlled current generation. Then, we will evaluate orbit elevation and orbit maintenance in actual operation.

Next, we will describe the prototype of a carbon nanotube tether, its performance evaluation, and the results of an extension experiment using a reel mechanism using an air flotation device. The tether length is assumed to be about 1 km based on the simulation results described above, and assuming extension over that distance, we have taken into consideration the motion when initial velocity is obtained at the beginning of extension, and the rebound at the end of extension. evaluate. The reel mechanism used is an improved version of the reel mounted on the STARS-X which was developed by Shizuoka University for the purpose of non-conductive tether extension.

Finally, the micro-satellite design based on these results has been described.

THE SEVENTH INTERNATIONAL CONFERENCE ON TETHERS IN SPACE

(June 3rd, 2024)

ABSTRACT

Session 4 – EDT & E-Sail

Chair: Prof. Arun Misra

Paper No: 2024040
7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Electric Sail Design Sensitivities

J. Inness[1], A. Houin[2], D. Tyler[3], J. Shah[4]
1 NASA Marshall Space Flight Center, Huntsville AL, USA, john.p.inness@nasa.gov
2 NASA Marshall Space Flight Center, Huntsville AL, USA, aaron.j.houin@nasa.gov
3 NASA Marshall Space Flight Center, Huntsville AL, USA, jaysal.r.shah@nasa.gov
4 NASA Marshall Space Flight Center, Huntsville AL, USA, daniel.a.tyler@nasa.gov

Conference Topic: Electric Sails for Interplanetary Exploration and Science

Electric Sails (E-Sails) are a promising propulsion technology that seek to enable high characteristic propellentless acceleration for spacecraft to reach distant and/or difficult to reach orbits such as rapid transit to heliopause. The E-Sail system exchanges momentum by using positively charged electrostatic tethers to repel solar wind photons to push it through space. This concept was first theorized by Pekka Jaunhuun in 2004 with further developments occurring including a NASA Innovative Advanced Concepts Phase 1 and Phase 2 hosted out of NASA's Marshall Space Flight Center (MSFC) [1]. These developments led to further maturation of the overall system, and this paper is designed to help identify different design sensitivities of an integrated Electric Sail system. To approach this, a small team at MSFC took an in-house developed three degrees of freedom (3DoF) simulation tool and a trajectory modelling tool to look at different design parameters and to determine a potential ideal E-Sail configuration.

An E-Sail system has different design architectures including a barbell design, hub and spoke design, and a potential hybrid solution. The barbell design features two equally massed satellites that spin around a central point in the tether system. The hub and spoke design features a large central spacecraft with small end spacecraft to aid in formation control of the overall E-Sail system. Leveraging elements from both the hub and spoke, and barbell design, a hybrid option exists where one could have a larger central mass and one or two tethers extended to a smaller end mass. In summary, the hub and spoke design is the ideal configuration for E-Sail with tethers spanning kilometers to achieve the designed design characteristic acceleration of at least one mm/s^2 with this architecture being the focus of this study.

Different key design parameters were varied as part of this study. These parameters include the total number of tethers, the length of the tethers, spin rate, relative spacecraft mass, tether voltage, inertia per tether, and impact of slew rate changes. These results started from an internal MSFC technology demonstration mission design and then the parameters were varied with engineering judgement to ensure that the results were consistent with expected results. These were varied in the MSFC 3DoF tool and compared to baseline results to generate a candidate ideal E-Sail design system. These results were then used to help inform the mission analysis design for the system.

The 3DoF trajectory optimization was performed in the Astrodynamics and Space Science Enabling Toolbox (ASSET) and utilized collocation optimization of control vector pointing with the objective function being transfer duration. A representative model of the E-Sail force was derived as a function of the Sun-pointing vector direction. This model was initialized with a zero Sun Incidence Angle (SIA) trajectory for the initial guess generation, then with a portion of the mission optimized SIA time history for fast outbound transfers. After the trajectory is hyperbolic relative to a heliocentric frame, the SIA is maintained at 0 degrees except for any needed trajectory correction maneuvers. This trajectory optimization looked at different characteristic acceleration values to analyze the impact it had on mission performance.

As a result of this study, the team can best inform mission designers and technology development efforts to mature the E-Sail system. This study will allow mission designers to have defined rules-of-thumb to design an E-Sail system to meet desired mission needs as well as providing several sample mission profiles. These design drivers will inform maturation efforts on which design requirements to consider for an integrated E-Sail design.

References

[1] Janhuenen, P. "Electric Sail for Spacecraft Propulsion", Aerospace Research Center, Vol 20, No. 4, 2004.

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Optimal Control Approach for Stable E-Sail Transitions

G. Pacheco-Ramos[1], R. Vazquez[2], D. Garcia-Vallejo[3]
1. Department of Aerospace Engineering, Universidad de Sevilla, Seville, Spain, gpacheco@us.es
2. Department of Aerospace Engineering, Universidad de Sevilla, Seville, Spain, rvazquez1@us.es
3. Department of Mechanical Engineering and Manufacturing, Universidad de Sevilla, Seville, Spain, dgvallejo@us.es

Conference Topic: Mathematical Modeling of Space Tethers, Dynamics, Controls.

Over the past two decades, Electric Solar Wind Sails (E-Sails) have emerged as a promising propulsion technology for space exploration missions. Utilizing the momentum of the solar wind, E-Sails deploy a mesh of wires to generate electric fields, enabling propellantless propulsion [1]. This technology offers significant advantages, including extended mission durations and potential applications in various space missions, such as small-body exploration, multi-target exploration, and establishing artificial equilibrium points in space environments [2].

Existing studies on trajectory optimization and guidance, some considering the uncertainty in the solar wind, indicate the need for adaptive operation throughout a mission. This involves varying the electric voltage at which the cables are modulated (requiring multiple on/off events for interplanetary missions) and executing maneuvers to modify the attitude of the E-Sail and hence the orientation of the generated propulsive force. Furthermore, various publications have analyzed the dynamics of the E-Sail, commonly considering steady-state operation characterized by: constant and equal voltage for all the tethers, constant attitude only modified by rotation around the longitudinal axis of the sail with constant angular velocity, and constant cable position with respect to the body-fixed coordinate system [3]. However, there is currently a gap regarding the feasibility of achieving stable and progressive power-up of the E-Sail to ensure its evolution to steady-state situation.

This work introduces a method for computing the optimal control law to facilitate the transition of the E-Sail between two steady states, corresponding to distinct voltage levels in the tethers. Leveraging principles of dynamics inversion applied to the E-Sail model, this innovative controller enables adjustments in propulsive force to meet the demands of optimal trajectory planning and guidance algorithms.

The architecture considered for the E-Sail is that of a central vehicle and radial tethers stabilized by the spin of the entire assembly and the presence of a remote unit at the outer end of the cables. The E-Sail dynamics is considered through a modeling approach that treats it as a multibody system (MBS). In contrast to [4], this work considers a minimum set of local coordinates formulation that leads to an ordinary differential equations (ODE) system. Selected coordinates include Euler angles to describe the attitude of the central spacecraft, angular rates expressed in body axes to depict the angular motion of the system, and angular magnitudes to establish the local orientation and position of the tethers.

The calculation of the control law is posed as an optimal control problem (OCP), which is solved using the direct transcription method, resulting in a nonlinear programming (NLP) problem. The cost function is established in terms of system coordinates and controls, allowing for bounded evolution of variables associated with internal dynamics while minimizing control requirements. The fourth order Runge-Kutta integration scheme used constitutes the nonlinear equality constraints that the optimization problem solution must satisfy. Additionally, once the reference trajectory and open-loop optimal control are determined, the tracking problem is addressed through a Receding Horizon Model Predictive (RHMPC) approach.

It is noteworthy that unlike proposals in other works, this study does not consider the application of control forces on remote units [2]. This fact complicates the system dynamics control as it reduces the control variables. However, it is considered an advantage as it simplifies the complexity of remote units by not having to be equipped with small thrusters, reinforcing the propellantless nature of the E-Sail.

The study's findings on a typical E-Sail configuration illustrate that stable evolution between equilibrium states can be achieved by appropriately combining temporal evolution of control moments and electric voltage in the tethers. Furthermore, the use of an optimal control problem formulation is confirmed to be an efficient and flexible strategy for resolving the inversion problem of the proposed E-Sail multibody model, despite its non-minimum phase dynamics and substantial size. Finally, the applicability of RHMPC algorithms is proven for the system tracking during the transitioning.

References

[1] Janhunen P. "Electric sail for spacecraft propulsion", Journal of Propulsion and Power, 20 (4), pp. 763 - 764, 2004, doi: 10.2514/1.8580.

[2] Bassetto, M., Niccolai, L., Quarta, A.A., Mengali, G. "A comprehensive review of Electric Solar Wind Sail concept and its applications", Progress in Aerospace Sciences, Vol. 128, 100768, 2022, doi: 10.1016/j.paerosci.2021.100768.

[3] Bassetto, M., Niccolai, L., Quarta, A.A., Mengali, G. "Attitude dynamics of an electric sail model with a realistic shape", Acta Astronautica, Vol. 159, pp. 250-257, 2019, doi: 10.1016/j.actaastro.2019.03.064.

[4] Pacheco-Ramos, G., Garcia-Vallejo, D., Vazquez, R. "Formulation of a high-fidelity multibody dynamical model for an electric solar wind sail", International Journal of Mechanical Sciences, Vol. 256, 108466, 2023, doi: 10.1016/j.ijmecsci.2023.108466.

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June 2-5, 2024, Toronto, ON, Canada

PERSEI SPACE: a new company on space tethers

Gonzalo Sánchez-Arriaga[1]
1 Department of Aerospace Engineering, Universidad Carlos III de Madrid, Madrid, Spain, gonsanch@ing.uc3m.es

Conference Topic: Electrodynamic tether technology

After developing the E.T.PACK and E.T.PACK-F projects, funded by the European Innovation Council with a total budget of 5.5 M€ and aimed at the development of a deorbit device based on electrodynamic tether technology, several team members of the consortium decided to create the company PERSEI Space (PRS) with the goal of move the technology from the lab to the market. The most important achievements of PRS since its foundation in September 2023 are its admission in the ESA-BIC programme, IP transfer from UC3M, and its first contract with a large satellite integrator. The company is currently negotiating with a private investor and submitted a NEOTEC proposal to the Spanish government. At a product level, PRS can provide services on analysis of missions with electrodynamic tethers (bare, bare-photovoltaic, and low-W) by using BETsMA v2.0 software to research groups and companies. and will start the development of devices for deorbiting, reboost, and in-orbit servicing by using electrodynamic tethers.

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Overview of Electron Emitter Technology Development at TU Dresden for the Application in Electrodynamic Tether Systems

Elisabeth Berka[1], G. Hentsch[2], Jan-Philipp Wulfkühler[3], M. Tajmar[4]
[1] Technische Universität Dresden, Institute of Aerospace Engineering, Dresden, Germany, elisabeth.berka@tu-dresden.de
[2] Technische Universität Dresden, Institute of Aerospace Engineering, Dresden, Germany, georg.hentsch1@tu-dresden.de
[3] Technische Universität Dresden, Institute of Aerospace Engineering, Dresden, Germany, jan-philipp.wulfkuehler@tu-dresden.de
[4] Technische Universität Dresden, Institute of Aerospace Engineering, Dresden, Germany, martin.tajmar@tu-dresden.de

Conference Topic: Space Tether Technology Development and Experimental Studies - Subsystem Technologies to Enable Space Tether Missions

At the Institute of Aerospace Engineering at TU Dresden a broad range of electron emitters for space applications is under development. Active electron emitters are required on most spacecraft to keep them neutral or as an integral part of an electric propulsion system. Most concepts for electrodynamic tethers rely on an active electron emitter to act as a cathode to return the electron flow through the tether into the environment plasma. Typical technologies are thermionic emitters, field emitters and hollow cathodes. We will present an overview of recent technological developments of field emitter and hollow cathode technology at our institute.

CNT field emitters developed at TUD have gained space heritage on the UWE-4 CubeSat mission [1] and successfully demonstrated an emission efficiency of 0.8 mA/W in a 1450 h endurance test at 500 µA [2]. With our latest development of a radial electron emitter [3], we were able to further increase the emission current and efficiency. So far, in tests lasting several hundred hours, we have achieved an efficiency of 1.6 mA/W with emission currents of 1.5 mA.

At the same time, we are working on the development of electron emitters based on diamond-like carbon layers (DLC). This material promises a high level of robustness and therefore a long lifetime. In initial experiments, we were able to show that the activation of layers with a very high sp^3 content by high voltages leads to promising emission properties [4]. We want to realize high-performance cathodes by activating such DLC layers over a large area.

A class of specialized hollow cathodes has been under development at TUD since 2015. They all share the low work function material C12A7 electride as a thermionic insert that can be operated without a heater. Emission currents have been demonstrated within the 0.3 to 5 A range.

Within the Horizon 2020 (H2020) Future Emerging Technologies (FET) OPEN Project E.T.PACK and its successor E.T.PACK-F, a version of the cathode is currently being developed to be operated on an in-orbit-demonstration mission of an electrodynamic tether demonstrator. The mission requires stable electron emission in the 0.3 A range with a low power consumption of just 20 W. To meet this requirement, a cathode system including a storage system for the krypton expellant and operating electronics are currently being developed. [5][6]

This paper will present the most recent developments of all three emitter technologies in the context of the application for electrodynamic tether technologies.

References

[1] A. Kramer, P. Bangert, and K. Schilling, “SSC19-WKI-02 Hybrid attitude control onboard UWE-4 using magnetorquers and the electric propulsion system NanoFEEP,” no. August 2020, 2019.

[2] J.-P. Wulfkühler, P. Laufer, M. Tajmar: “Emission characteristics and 1250h endurance test of a cold electron field emitter based on CNTs for space applications”, Space Propulsion 2021 Conference, Digital, 17-19 March 2021, p. #00117.

[3] G. Hentsch and M. Tajmar, "Development of CNT Cathodes for Space Applications," 2023 IEEE 36th International Vacuum Nanoelectronics Conference (IVNC), Cambridge, MA, USA, 2023, pp. 100-102.

[4] G. Hentsch, M. Tajmar and V. Weihnacht, "Field Emission Properties of Highly Conductive Diamond-Like Carbon Layers," 2023 IEEE 36th International Vacuum Nanoelectronics Conference (IVNC), Cambridge, MA, USA, 2023, pp. 125-127.

[5] L. Tarabini Castellani, S. Garcia-Gonzalez, A. Ortega, S. Madrid, E. C. Lorenzini, L. Olivieri, G. Sarego, A. Brunello, A. Valmorbida, M. Tajmar, C. Drobny, J-P.

Wulfkühler, R. Nerger, K. Wätzig, S. Shahsavani, G. Sánchez-Arriaga, “Deorbit Kit Demonstration Mission”, 72nd International Astronautical Congress (IAC), 25-29 October 2021, Dubai, United Arab Emirates.

[6] C. Drobny, J.-P. Wulfkühler and M. Tajmar, “Characterization of a Low Current Heaterless C12A7 Electride Hollow Cathode for an Electrodynamic Tether Deorbiting Device”, 37th International Electric Propulsion Conference, 19-23 June 2022, Massachusetts Institute of Technology, Cambridge, USA.

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Hardware Emulator of a Short Electrodynamic Tether

Angel del Pino Jiménez[1], Amadeo Velasco[2], Gonzalo Sánchez Arriaga[3]
[1]Universidad Carlos III de Madrid, Aerospace Engineering Department, Leganés, Spain, angel.delpino@uc3m.es
[2]Sener Aeroespacial, Tres Cantos, Madrid, Spain , amadeo.velasco@aeroespacial.sener
[3]Universidad Carlos III de Madrid, Aerospace Engineering Department, Leganés, Spain, gonzalo.sanchez@uc3m.es

Conference Topic: Space Tether Technology Development and Experimental Studies

Electrodynamic tethers (EDTs) typically involve an electronic box between the conductive tether and the electron emitter. In the case of using a hollow cathode (HC), such electronics are in charge of controlling the current level and the voltages of the emitter and the keeper. Modelling the tether-electronic-emitter-plasma circuit, which can be done through software simulations or hardware emulators, is essential to study its behaviour and size the electric elements. In the case of tethers, a detailed electric model was developed in the past based on numerical and experimental analysis of its interaction with the ambient plasma [1]. Regarding the electronics, an electric power module that involves batteries, a power conditioning, and dumping resistors was proposed [2]. It was designed to operate the HC and make power harvesting (several kilowatts) with a 20 km long tether. In the opposite limit of short EDTs, a circuit model for miniaturized EDT systems was presented [3]. It considers a few meters long EDTs for both reboost and deorbiting, and it requires 100s' milliwatts to operate their low-power and expellant-less electron emitters.

This work presents an electrical model for an EDT system in an intermediate range of power and current. In particular, it applies for a tape EDT of 500 m of length equipped with a HC that cannot operate with current below 0.2 A. Additionally, due to tether dynamic considerations, current at the emitter should be lower than 0.5 A. As shown in Fig. 1, the proposed model involves the EDT, an electronic box and the HC. The I-V characteristics curve of the EDT was taken from a bare tether model [4], and the I-V curves of the emitter and the keeper were taken from direct measurement in the laboratory [5] and here substituted by linear regressions. As shown in Fig. 1, the proposed electronic box has two power supplies and a resistor to guarantee the minimum and maximum current constraints. A software was developed to implement the electric model and study the power that should be provided/dissipated as a function of the motional electric field and the plasma density for a particular deorbit mission with an EDT.

The theoretical results were used to prepare a hardware emulator. The emitter was emulated by zener diodes that provides the target voltage drop ΔV_C, whereas the keeper was substituted by a variable resistor R_K. The EDT is emulated by a resistor R_T and a programable DC power supply. The programable power supply was controlled with a computer to mimic the temporal evolution of the ambient variables (motional electric field and plasma density) that the EDT finds during its mission. The hardware in the loop study allowed to understand the electric behaviour of the full EDT system and make a design of the power supplies and the resistor of the electronic box.

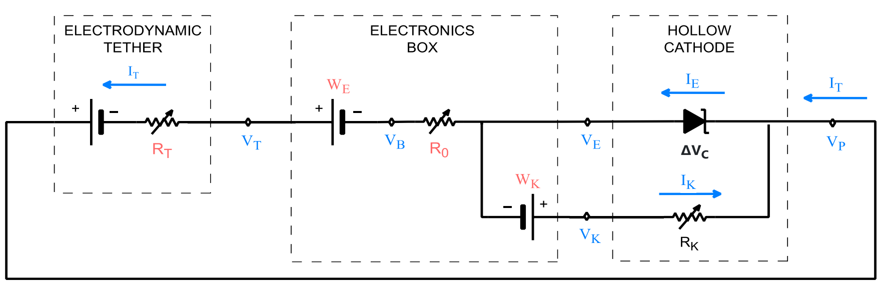

Figure 1: Electrodynamic tether hardware emulator

References

[1] Bilén, S. G. (1998) PhD Thesis: Pulse Propagation Along Conductors in Low-Density, Cold Plasmas as Applied to Electrodynamic Tethers in the Ionosphere
[2] Carrasco, J. A., García de Quirós, F., Alavés, H., & Navalón, M. (2020). Electric power module for a bare electrodynamic tether. Acta Astronautica, 177, 798–805. https://doi.org/10.1016/j.actaastro.2019.12.001
[3] Bell, I. C., Gilchrist, B. E., McTernan, J. K., & Bilén, S. G. (2017). Investigating miniaturized electrodynamic tethers for picosatellites and femtosatellites. Journal of Spacecraft and Rockets, 54(1), 55–66. https://doi.org/10.2514/1.A33629.
[4] Sanmartín, J. R., Martínez-Sánchez, M., & Ahedo, E. (1993). Bare wire anodes for electrodynamic tethers. Journal of Propulsion and Power, 9(3), 353–360. https://doi.org/10.2514/3.23629
[5] Drobny, C., Wätzig, K., Rost, A., & Tajmar, M. (2024). Endurance operation of a heaterless C12A7 electride plasma cathode and post operation material analysis. Acta Astronautica, 214, 231–239. https://doi.org/10.1016/j.actaastro.2023.10.002

THE SEVENTH INTERNATIONAL CONFERENCE ON TETHERS IN SPACE

(June 4th, 2024)

ABSTRACT

Session 5 - E-Sail & Space Tether

Chair: Prof. Gonzalo Sanchez-Arriaga

- **Title:** A Comprehensive Investigation of Electric Solar Wind Sail Coning Motion (2024018)
- **Title:** Iterative Learning Control for Multiple Deployment and Retrieval of Tethered Satellite System with Input Saturation (2024074)
- **Title:** Simple Velocity Planning Control of Space Tether Deployment (2024067)
- **Title:** Design and Application of Tethered Spacecraft Simulators (2024021)
- **Title:** Chaotic Behaviors of a Tethered Satellite System Induced by Longitudinal Oscillation (2024064)

Paper No: 2024018
7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

A Comprehensive Investigation of Electric Solar Wind Sail Coning Motion

Chonggang Du[1], Zheng H. Zhu[2]
1Xidian University, Xi'an, China, duchonggang@xidian.edu.cn
2 York University, Toronto, Canada, gzhu@yorku.ca

Conference Topic: Electric Sails for Interplanetary Exploration and Science

An electric solar wind sail (E-sail) is an innovative propellantless propulsion system that utilizes the solar wind dynamic pressure to generate propulsive force [1]. It offers several advantages over other propulsion systems, such as higher payload fractions, slower degradation of propulsive force over Sun-spacecraft distances, and easier-to-tune attitude control compared to solar sails. These characteristics make it a promising and compelling technology for deep space exploration missions. Unfortunately, the propulsive forces will cause the main tethers to periodically swing in and out of the spin plane, resulting in the so-called "coning motion" [1-2]. Given the prolonged operational lifetime of the E-sail and the small tether diameter, this continuous coning motion presents significant failure risks if it is not adequately controlled. Thus, to mitigate these risks, it is crucial to analytically explain the mechanism behind this periodic motion, and further determine the equilibrium state of the E-sail.

The objectives of this paper are to address the aforementioned challenges. Firstly, the paper reveals unknown mechanism underlying the periodic coning motion of the axially symmetric E-sail, as well as the analytic solution for its oscillation frequency and the upper bounds of the coning angle. Secondly, the paper determines the equilibrium state of the axially symmetric E-sail at an arbitrary sail angle. Finally, the examines the E-sail's ability to maintain its equilibrium state from an initial equilibrium configuration. The research presented in this study lays a solid foundation for the practical application of the E-sail system.

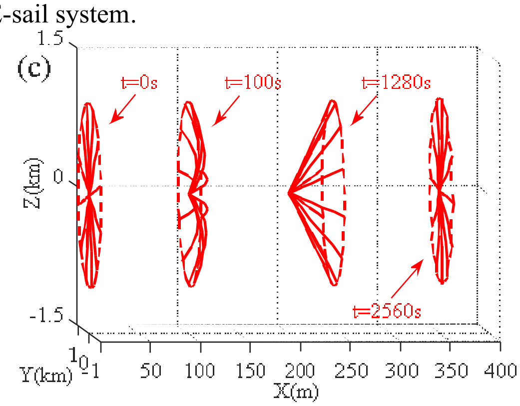

Figure 1. Temporal variations of E-sail coning motion in a period.

References

[1] Bassetto M., Niccolai L., Quarta A. A., Mengali G. "A comprehensive review of Electric Solar Wind Sail concept and its applications", Progress in Aerospace Sciences, 2022, 128, 100768.
[2] Du C. G., Zhu Z. H., Li G. Q. "Analysis of thrust-induced sail plane coning and attitude motion of electric sail", Acta Astronautica, 2021, 178: 129-142.

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7th International Conference on Tethers in Space
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Iterative Learning Control for Multiple Deployment and Retrieval of Tethered Satellite System with Input Saturation

Shouxu Chen[1], Ti Chen[1*], Weidong Chen[1], Caoqun Luo[1]
1 State Key Laboratory of Mechanics and Control for Aerospace Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China, hxzbcra@nuaa.edu.cn (Shouxu Chen), chenti@nuaa.edu.cn (Ti Chen), chenwd@nuaa.edu.cn (Weidong Chen), maillcq@nuaa.edu.cn (Caoqun Luo)

Conference Topic: Fundamental Research on Space Tethers

Tethered satellite system (TSS) has drawn great attentions from international space agencies and organizations in recent years due to its potential applications to space missions. To achieve a goal of on-orbit sustainable utilization, it is expected that TSS systems can be capable of executing multiple deployment and retrieval processes, which can be seen as a repetitive task.

Iterative learning control (ILC) is widely used in engineering, especially in repetitive processes. This paper aims to develop an ILC-based tension control law for the multiple deployment and retrieval processes of a TSS with input saturation. The tether length rate is selected as the iterative learning term to facilitate the multiple deployment and retrieval processes. To prove the proposed control strategy, a detailed stability analysis of the closed-loop system is proved via Lyapunov function and LaSalle’s invariance principle. When the libration angle of the tether exceeds 90 degrees, the contacts and entanglements between tethers and satellites may result in tumbling motions or even cause mission failure with tether being cut off. To address this problem, a constraint on the initial value of the Lyapunov function is imposed to limit the libration angle in an acceptable range. Based on the system’s energy function, the learning convergence is strictly demonstrated that the controller will converge along the iteration axis.

Finally, numerical simulations are presented to verify the effectiveness of the controller by comparisons with the controller in [1]. The results demonstrate its capability to improve performance by learning from past control experiences.

The main contributions of this article are given as follows.

1) Compared with the analytical control schemes for deployment or retrieval of TSS in [2] and [3], the proposed controller in this article can compensate for the disturbances utilizing the consensus task repetition.

2) Different from the ILC designed for systems with input saturation in [4], the proposed control plant is a single-input/multiple-output system, which takes the tether tension as the only control input.

References

[1] Wen, H., Zhu, Z., Jin, D., and Hu, H. "Space tether deployment control with explicit tension constraint and saturation function." Journal of Guidance, Control, and Dynamics, Vol. 39, pp. 916-921, 2016, doi: 10.2514/1.G001356.
[2] Xu, S., Sun, G., Ma, Z., and Li, X. "Fractional-order fuzzy sliding mode control for the deployment of tethered satellite system under input saturation." IEEE transactions on aerospace and electronic systems, Vol. 55, pp. 747-756, 2018, doi: 10.1109/TAES.2018.2864767
[3] Ma, Z., and Sun, G. "Adaptive sliding mode control of tethered satellite deployment with input limitation.", Acta Astronautica, Vol. 127, pp. 67-75, 2016, doi: 10.1016/j.actaastro.2016.05.022
[4] Sebastian, G., Tan, Y., and Oetomo, D. "Convergence analysis of feedback-based iterative learning control with input saturation.", Automatica, Vol. 101, pp. 44 - 52, 2019, doi: 10.1016/j.automatica.2018.11.045.

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7^{th} **International Conference on Tethers in Space**
June 2-5, 2024, Toronto, ON, Canada

Simple Velocity Planning Control of Space Tether Deployment

Junjie Kang[1], Jinjun Shan[1]
York University, Toronto, Canada

Conference Topic: Fundamental Research on Space Tethers.

The success of space tether missions is contingent upon achieving precise and stable deployment. Velocity control has been widely employed for tether deployment; however, it may lead to the residual libration motion at the final stage. To mitigate libration motion, various studies have explored the design of the term $\dot{l}/l = \dot{\theta}/\left(\dot{\theta}+1\right)$ for the libration dynamics as follows,

$$\ddot{\theta} + 2\frac{\dot{l}}{l}\left(\dot{\theta}+1\right) + 3\sin\theta\cos\theta = 0 \tag{1}$$

where l denote the normalized tether length, and θ denotes the tether libration angle. It can be easily observed that this design can effectively damp the libration motion. However, this approach could potentially lead to a deviation of the final tether length from the desired length.

Thus, this study will introduce a novel approach to address this critical requirement through a straightforward yet efficient velocity planning control design for real-time space tether deployment. The primary aim is to guarantee that the deployed tether achieves the desired length while significantly suppressing the libration motion. The velocity is designed two parts: The first part is a time-varying nominal trajectory, such as an exponential curve, which guides the tether length deploying to the desired length. The second part involves an anti-swing design to suppress the libration motion.

Subsequently, by applying the Lyapunov-based stability analysis, it can be demonstrated that the tether length will deploy to its desired constant, and the tether libration angle can be effectively suppressed, locally stabilized to zero under certain condition. Furthermore, a modified velocity planning algorithm is presented to ensure the libration angle remains within a safe region.

In what follows, a predesigned nominal trajectory is required to have the following properties:

1) The nominal trajectory $l_n(t)$ is sufficiently smooth and bounded, and

$$\lim_{t\to\infty} l_n(t) = c_d \tag{2}$$

where $c_d \in \mathcal{R}^+$ is the desired length.

2) The velocity of nominal trajectory is bounded, and $\dot{l}_n(t) \in \mathcal{L}_2 \cap \mathcal{L}_\infty$,

$$0 \le \dot{l}_n(t) \le v_d \tag{3}$$

where $v_d \in \mathcal{R}^+$ denotes the maximum velocity of tether deployment. For example, $l_n(t) = c_0 + (c_d - c_0)(1 - e^{-kt})$.

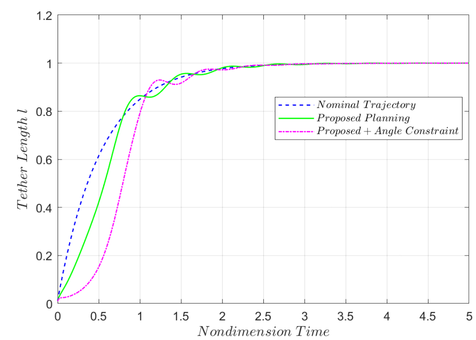

Figure 1. Length profiles

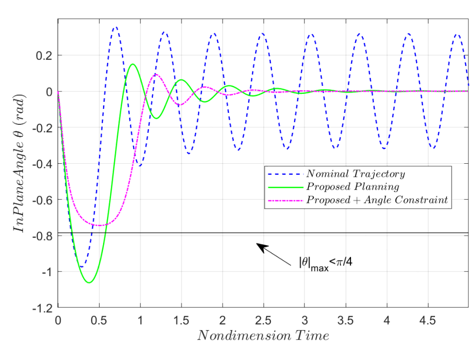

Figure 2. Libration angles

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June 2-5, 2024, Toronto, ON, Canada

Tethered Space Tug Simulators

E. Jaynes[1], J. Inness[2]
1 NASA Marshall Space Flight Center, Huntsville AL, USA, emma.k.jaynes@nasa.gov
2 NASA Marshall Space Flight Center, Huntsville AL, USA, john.p.inness@nasa.gov

Conference Topic: Space Tether Technology Development and Experimental Studies

Small, tethered spacecraft, or space tugs, are a promising space capability. They can be deployed on tethers and used for a wide variety of in-space activities; a large portion of which fall under in-space servicing, assembly, manufacturing (ISAM) functions. This includes functions such as structural mating and assembly, servicing, proximity operations, capture, docking, mating, and relocation. However, there is a great deal of work to be done to raise the Technology Readiness Level (TRL) of the capabilities needed to fully realize these capabilities.

The Flat Floor Robotics Lab (FFRL) at NASA's Marshall Spaceflight Center (MSFC) has been working on space tug development for several years. The eponymous floor is 44 by 86 feet, made from a self-leveling epoxy. This creates an extremely smooth surface that air bearings can float on with very little friction, creating a simulation of zero gravity in a two-dimensional plane. The lab has several platforms of various sizes that act as vehicle simulators for testing sensors, control algorithms, mechanisms, etc. One of these platforms is a small spacecraft simulator, which can be tethered to simulate a space tug.

In the last several months, the FFRL team has been working with MSFC's welding group to conduct a laser beam welding demonstration on air bearing platforms. This demo is utilizing a space tug simulator to fly up to a floating weld platform, where two parts are clamped together and laser welded. The space tug simulator has an air bearing to provide float, as well as several actuated air thrusters to provide propulsion and make the simulator maneuverable. Currently, flights of this simulator are completed by a human operator. An RF hand controller sends signals to both actuate and fire three sets of thrusters on the simulator. This makes any maneuvers of the space tug highly subject to human error, and operators must have dedicated practice time before being able to perform maneuvers with any sufficient reliability. For the current laser welding demonstration, human operated performance is sufficient, but future implementations of in-space welding and other ISAM efforts will require higher precision, reliability, and autonomy.

MSFC has funded a project that will allow a small team in the FFRL to develop the next generation of space tug simulator, which will be automated. Closed loop control will allow a user to command a position, or set of positions, that the simulator will be able to "fly" to on its own. This Maneuverable Automated Tethered Spacecraft Simulator (MATSS) will have configurable design, to allow a variety of payloads and mission configurations to be demonstrated on the air bearing floor. This will be an invaluable test bed for low and mid TRL advancement for space tether mission subsystems, such as more advanced demonstrations of in-space welding. Once one MATSS is constructed and demonstrated effectively, several more can be built, enabling more advanced tether missions; Electric Sail test beds, sensor arrays, and other science-enabling missions.

This paper will detail the design and test of the FFRL's MATS simulator, including efforts to establish closed loop control and autonomous capabilities. It will also detail use cases for this technology, and how it will further develop both develop science and exploration missions.

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June 2-5, 2024, Toronto, ON, Canada

Chaotic Behaviors of a Tethered Satellite System Induced by Longitudinal Oscillation

B. S. Yu[1], J. T. Chen[2]
[1] State Key Laboratory of Mechanics and Control for Aerospace Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, China, yu_bensong@nuaa.edu.cn
[2] State Key Laboratory of Mechanics and Control for Aerospace Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, China, JingtianChen@nuaa.edu.cn

Conference Topic: Mathematical Modeling of Space Tethers, Dynamics, Controls

With an increasing number of orbital missions, a tethered satellite system as a novel and potential practical tool has attracted more attention from researchers. The operating characteristics of such a system, including its high reliability, low cost and reusability, would play an important role in the future aerospace industry. The existence and identification of chaos regarding in-plane pitch motions of the tethered satellite system are scientific problems of concern, and are directly related to normal system operations in the station-keeping phase. This paper investigates the impact of microamplitude longitudinal oscillation on the appearance of chaos in the tethered system under atmospheric perturbations. To describe the dynamic characteristics of the on-orbit system, a series of reference coordinates is introduced. A simplified rod model which considers tether elasticity and satellite masses is considered. It is assumed that both satellites are slender cylinders, one end of which is connected to the space tether. And, a flexible tether model is also established to validate the dynamic behaviors of the simplified model. The Melnikov method which is a necessary but not sufficient condition is employed to identify a criterion that can predict chaos. Chaos would appear as shown in Fig. 1, provided that the stable and unstable manifolds in the phase plane intersect transversally, which can be identified when the ratio between the perturbation parameters is less than a critical value concerning the oscillation frequency of an elastic tether. As shown in Fig. 2, a chaotic zone is proposed to help identify existing chaos. Then the cell mapping method is utilized to describe the system's global dynamics, including chaos. Numerical results indicate that a higher orbital altitude and a larger amplitude, i.e., a lower atmospheric density and a lower stiffness tether, contribute to the appearance of chaotic motions. It is proven that the dynamics of the system are dependent upon system parameters, such as satellite attitudes, mass distribution and tether length. Additionally, a flexible tether model is structured in the form of discrete elements to verify the chaotic motion that occurs in an elastic rod model. The motion is also validated and presented in a global dynamics analysis using the cell mapping algorithm. Therefore, it is concluded that perturbations might result in chaos for tethered satellites.

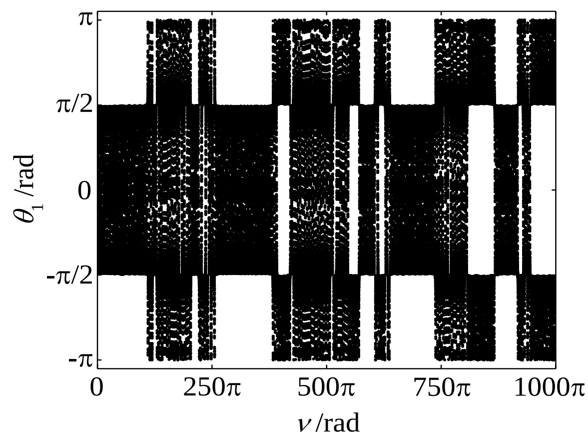

Fig. 1 Chaotic motion

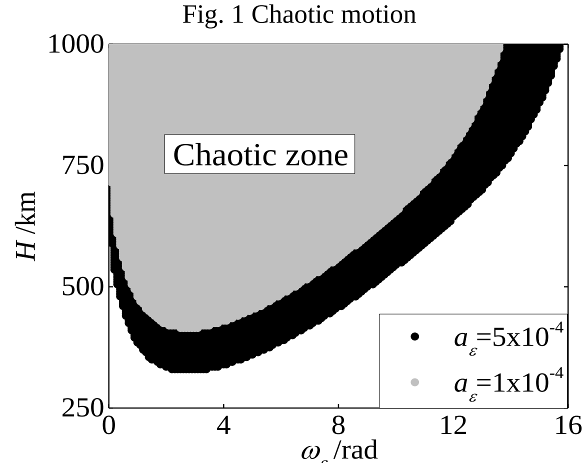

Fig. 2 Chaotic zone

THE SEVENTH INTERNATIONAL CONFERENCE ON TETHERS IN SPACE

(June 4th, 2024)

ABSTRACT

Session 6 - Space Tether & EDT

Chair: Prof. Martin Tajmar

- **Title:** Experimental Test and Numerical Validation for Evaluating the Dynamics of the In-Line Dumper for the E.T.PACK-F Project (2024051)
- **Title:** Satellite Attitude Motion Analysis of Three-Body Tethered System During Its Deployment Process Using Method of Integral Manifolds (2024008)
- **Title:** Calculation and Control of Equilibrium Position of Bare Electrodynamic Tether System (2024013)
- **Title:** Ground Experimental Study on A Mechanism for Repeatable Deployment and Retrieval of a Two-Body Tethered Satellite System (2024073)
- **Title:** Along-Track Deployment Control of Space Tether System for SAR-GMTI Mission (2024007)

Paper No: 2024051
7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Experimental test and numerical validation for evaluating the dynamics of the In-Line Dumper for the E.T.PACK-F project

G. Polato[1], M. Urbinati[2], A. Valmorbida[3], S. Chiodini[4], G. Colombatti[5], G. Anese[6], A. Brunello[7], E.C. Lorenzini[8]
[1]Dep. of Industrial Engineering (DII), University of Padova, Padova, Italy, giulio.polato@studenti.unipd.it
[2]Dep. of Industrial Engineering (DII), University of Padova, Padova, Italy, matteo.urbinati@studenti.unipd.it
[3]Dep. of Industrial Engineering (DII) and CISAS "G. Colombo", University of Padova, Padova, Italy, andrea.valmborbida@unipd.it
[4] Dep. of Industrial Engineering (DII) and CISAS "G. Colombo", University of Padova, Padova, Italy, sebastiano.chiodini@unipd.it
[5]Dep. of Industrial Engineering (DII) and CISAS "G. Colombo", University of Padova, Padova, Italy, giacomo.colombatti@unipd.it
[6] CISAS "G. Colombo", University of Padova, Padova, Italy, giovanni.anese@studenti.unipd.it
[7] CISAS "G. Colombo", University of Padova, Padova, Italy, alice.brunello.3@studenti.unipd.it
[8] Dep. of Industrial Engineering (DII) and CISAS "G. Colombo", University of Padova, Padova, Italy, enrico.lorenzini@unipd.it

Conference Topic: Space tether Technology Development and Experimental Studies – Subsystem Technologies to Enable Space Tether Missions

In the last few decades, the escalating challenge of man-made space debris has raised serious concerns for the success of future space missions and the space community has turned its attention to innovative "green" deorbiting technologies. One standout solution in this category is Electrodynamic Tethers (EDT), which offer significant potential due to their passive and fuel-free attributes. Particularly noteworthy is their effectiveness in addressing the pressing issue of space debris in low Earth orbit (LEO).

The E.T.PACK-F project [1], funded by the European Innovation Council (EIC), aims to build a TRL 9 product prototype, called Deorbit Kit, incorporating ETD technology to safely deorbit end-of-life satellites. The device comprises two modules: the first one accommodates the deployment mechanism (DMM) and the second one hots the hollow cathode electron emitter (EMM). The flight model is scheduled for launch in 2025. Once in orbit, a few hundreds-meter-long aluminum tape will be deployed, and the electron emitter will be activated to enable current flow in the tether. This process generates a drag Lorentz force through interaction with the geomagnetic field, effectively aiding in the deorbiting of the satellite.

While deorbiting satellites, the Lorenz force induces oscillations in the tether (libration) that progressively increase over time, posing a risk of pushing the system into an unstable configuration (flip upside down) before its reenter in the atmosphere. As partner of the E.T.PACK-F consortium, the University of Padua has developed a passive mechanical device called In-Line Damper (ILD) for mitigating the libration of the tether [2] and reducing the longitudinal stiffness. The ILD's presence impacts the dynamics of the two modules connected by the tape-shaped tether during the initial phase of their separation. To ensure a successful separation, a thorough understanding of the ILD's influence on relative dynamics and the implementation of a suitable sequence of operations are essential.

Our research group has developed both software tools and laboratory setups to simulate and experimentally verify the initial phase of the E.T.PACK module separation. We created a Matlab program to simulate the complete dynamics of the two modules during the early separation phase. Specifically, both modules are modeled as rigid bodies with complete 6 degrees of freedom dynamics, and the tether is modeled as a sequence of lumped masses properly connected, accounting for the elastic and damping effects of the ILD. Regarding the laboratory setup, the unique SPARTANS facility [3] consists of two platforms able to move at low-friction on a 3 m by 2 m testing table thanks to an air-cushion system. This facility has been used to reproduce experimentally the dynamics of the In-line damper during the separation phase.

In this paper, we will present both numerical results obtained with the Matlab simulator and experimental results obtained with the SPARTANS facility. The objective is to provide data on the realistic behavior of the ILD during the separation phase, comparing the numerical results to the experimental data obtained with the SPARTANS facility of the University of Padova.

References

[1] http://www.etpack.eu
[2] International extension of patent (PCT), "DAMPER DEVICE AND CONNECTING APPARATUS", application number PCT/IB2022/060199. priority date 25/10/2021, inventors: L. Olivieri, E. C. Lorenzini, A. Valmorbida, A. Brunello, G. Sarego.
[3] Valmorbida, Andrea, et al. "SPARTANS-A cooperating spacecraft testbed for autonomous proximity operations experiments." *2015 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) Proceedings*. IEEE, 2015.

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7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Satellite Attitude Motion Analysis of Three-Body Tethered System during Its Deployment Process Using Method of Integral Manifolds

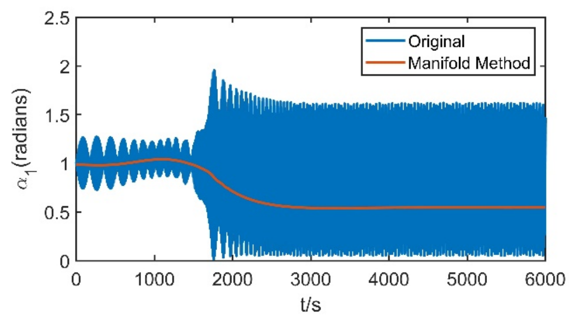
Y. Zhang[1], C. Wang[1], Y. Zabolotnov[2], A. Li[1], H. Lu[1]

1 School of Automation, Northwestern Polytechnical University, Xi'an, China, luhs@nwpu.edu.cn
2 Samara National Research University, Samara, Russia

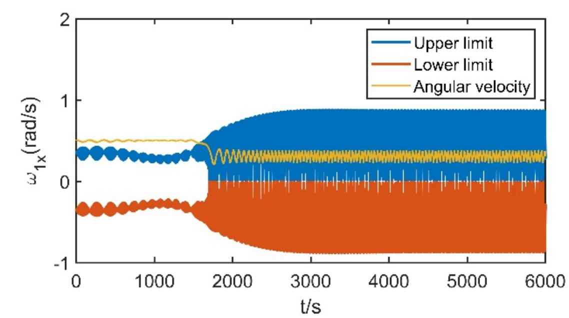
Conference Topic: Mathematical Modeling of Space Tethers, Dynamics, Controls

A typical linear three-body tethered system (LTBTS) comprises one primary satellite and two sub-satellites connected symmetrically by tethers[1]. Such systems can be used for various space missions including artificial gravity, tethered space observatories, interferometric telescopes, etc. Space experiments reveal that the deployment process is still a vulnerable stage even after decades of research. Various researchers have revealed that the system's inherent properties, such as deviations in tether connection points, initial disturbances, and the structural characteristics of the end bodies can lead to resonances and significant oscillations during the deployment process. In severe instances, this may lead to tether entanglement or breakage, ultimately disrupting the desired formation and resulting in mission failure.

Based on the problems above, this paper aims to analyze the impact of the unideal configuration of internal structure on the end-body's attitude motion during the deployment process. The deployment model of the LTBTS is established using the Lagrangian equations and the end-body's attitude is described using Eulerian angles. The initial formation of the LTBTS involves separating two subsatellites from the central main satellite in opposite directions, which results in the creation of a three-body configuration aligned with the system's centroid and the Earth's center. In the context of the aforementioned deployment process, this study investigates the impact of unideal internal system parameters on the attitude motion of end-bodies. We found that resonance phenomena of the angles of nutation and spin occur under errors in initial angles/angular velocities, offset errors of tether connection points, and unideal structural characteristics of the satellites. To obtain the analytical solutions of resonance, equations of angles of nutation is transformed and the satellite attitude equations are systematically solved using the method of integral manifolds[2]. Compared to commonly used methods for obtaining analytical solutions in dynamics, such as the averaging method or multiscale method, the method of integral manifolds can be employed to analyze situations involving large-angle variations. The potential resonance can be reduced by decreasing system asymmetry and initial interference. The effectiveness of the dynamic analysis is evaluated through simulations. It was found that, in cases of larger initial angular values of nutation (1 rad), the offset error of connection points should not exceed 5% to avoid resonance. However, in situations with smaller initial angular values of nutation (0.01 rad), resonance does not occur until offset error of 30%.



(a) Angle of nutation



(b) Angular velocities of satellite

Figure 1. Attitude motions of end-satellite under resonance case

Remark 1 In Figure 1(a), "Original" depicts the angle of nutation based on the original nolinear model, while "Intergral Manifold Method" illustrates the angle of nutation caculated using the intergral manifold method; In Figure 1(b), "Upper limit" and "Lower limit" denote the limits of angular velocity when resonance occurs between the angle of nutation and the angle of spin.

References

[1] Levin, E. M, Dynamic analysis of space tether missions, Advances in the Astronautical Sciences, Vol. 126, 2007.

[2] Zabolotnov, Y. M. Application of the integral manifold method to the analysis of the spatial motion of a rigid body fixed to a cable. Mechanics of Solids 51(4), 371-384 (2016). https://doi.org/10.3103/s0025654416040014

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7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Calculation and control of equilibrium position of bare electrodynamic tether system

M. Xie[1], C. Wang[1], H. Lu[1], A. Li[1], Y. Zabolotnov[2]

1 School of Automation, Northwestern Polytechnical University, Xi'an, China, luhs@nwpu.edu.cn
2 Samara National Research University, Samara, Russia

Conference Topic: Tether Propulsion and Energy Generation

The bare electrodynamic tether system (BEDT) is a propellant-free propulsion technology with high electron collection efficiency, which is considered an ideal platform for de-orbiting missions[1]. To BEDT, one of the core issues is to locate and maintain its equilibrium positions. However, due to the nonlinear distribution of electrical current, it is a challenging task to locate equilibrium positions for BEDTs. The conventional method of curve fitting[2], though accurate, cannot provide an analytical calculation of euiqillibrium positions. Therefore, for the convenience of dynamic analysis and controller design, it is still an unresolved problem to give an analytical calculation of equilibrium positions[3].

To address the challenge above, this paper studied the calculation of the BEDT equilibrium position and its stable control around the equilibrium position. First, a new methodology was proposed for calculating the equilibrium position of the bare electrodynamic tether system using integral variable substitution. This innovative methodology gives an analytical form of equilibrium positions, which avoids the limitations of the conventional curve-fitting method and thus allows further dynamic analysis and controller design. Second, based on the analytical calculation, the influence of key parameters like tether diameters, tether materials, and orbital parameters on the equilibrium positions was analyzed. Third, a control strategy for stabilizing BEDT around its equilibrium positions was proposed by adjusting tether length, which regulates angular moment and electrical current on tether at the same time. Compared to the conventional on/off strategy, the proposed strategy avoids the undesired transient responses or additional system disturbances, and stabilizes tether positions around equilibrium positions. Considering the change of geomagnetic field strength and electron density during de-orbiting, a sliding mode controller based on prescribed performance control was designed. Numerical simulation results indicate that the analytical calculation of the equilibrium positions matches the nonlinear model well with an error of less than 5% considering the high-precision magnetic field and ionosphere models. Tether is stabilized around the equilibrium position well under the regulation of the sliding mode controller, the angular deviation of which is less than 0.003 rad.

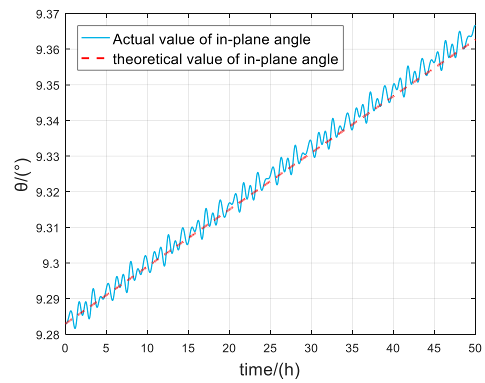

Figure 1. Actual value and theoretical value of In-plane angle without controller

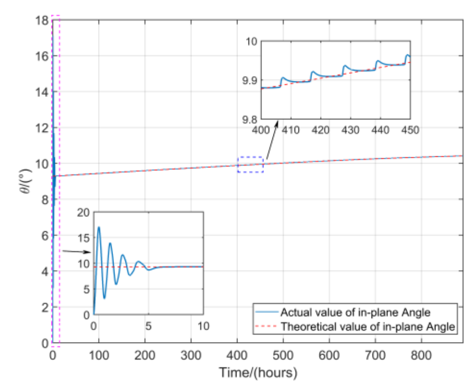

Figure 2. Actual value and theoretical value of In-plane angle with tether length control strategy

References

[1] C. Wang, G. Li, Z. H. Zhu, and A. Li, "Mass Ratio of Electrodynamic Tether to Spacecraft on Deorbit Stability and Efficiency", Journal of Guidance, Control, and Dynamics, vol. 39, no. 9, pp. 2192–2198, Sep. 2016, doi: 10.2514/1.G000429.
[2] B. S. Yu, P. B. Dai, and D. P. Jin, "Modeling and dynamics of a bare tape-shaped tethered satellite system", Aerospace Science and Technology, vol. 79, pp. 288–296, Aug. 2018, doi: 10.1016/j.ast.2018.05.046.
[3] H. Lu, A. Li, C. Wang, and Yu. M. Zabolotnov, "Stability analysis and motion control of spinning electrodynamic tether system during transition into spin", Acta Astronautica, vol. 177, pp. 871–881, Dec. 2020, doi: 10.1016/j.actaastro.2019.11.032.

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June 2-5, 2024, Toronto, ON, Canada

Ground Experimental Study on a Mechanism for Repeatable Deployment and Retrieval of a Two-Body Tethered Satellite System

Ti Chen [1*], Jie Yang[1], Shuo Chen[1], Dawei Feng[1], Yuzhe Wang[1]
1 State Key Laboratory of Mechanics and Control for Aerospace Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China, chenti@nuaa.edu.cn (Ti Chen), yangjie97@nuaa.edu.cn (Jie Yang), jsys_c@nuaa.edu.cn (Shuo Chen), bigfeng@nuaa.edu.cn (Dawei Feng), 3247108685@qq.com (Yuzhe Wang)

Conference Topic: Space Tether Technology Development and Experimental Studies; Subsystem Technologies to Enable Space Tether Missions Tether Propulsion.

With the advancement of tethered satellite systems, future missions based on tethered satellite operations may need multiple deployments and retrievals. For example, a service spacecraft may be able to collect some space debris [1],[2]. Hence, this study focuses on designing a mechanism for the efficient deployment and retrieval of sub-satellites.

Numerical simulation of the deployment and retrieval is presented in this paper to provide a theoretical basis for ground experiments, particularly under various extreme conditions [3]. It is assumed that the sub-satellite is a non-cooperative target and there is no direct measurement of the sub-satellite. Hence, the motor tracks an open-loop optimal trajectory during the experiment in this paper.

As shown in Figure 1, the mechanism is divided into two components: the ejection part and the tether deployer. The ejection part consists of a spring and a docking guide cone. The spring provides the needed energy for ejection, while the docking guide cone ensures the sub-satellite's attitude during retrieval. To enable autonomous on-orbit operations of the system, a novel automatic locking and unlocking mechanism is designed. The tether deployer consists of a motor, a reel, a tether distributor, and a tether feeder, which are connected by gears. The design of the tether distributor is inspired by the line-discharging method of a fishing reel. It utilizes a reciprocating screw and guide rod in conjunction with a slider to achieve the back-and-forth motion of the slider, thereby driving the tether to be uniformly distributed on the reel during the retrieval process. The tether feeder consists of two rods and rubber wheels. The two rubber wheels grip the tether tightly. During the deployment process, the tether is pulled out by rotating the rubber wheels to prevent tangling of the tether around the reel. Additionally, the mechanism employs one-way bearings to prevent the tether feeder from feeding the tether into the mechanism during retrieval and to minimize the friction caused by the sliding motion of the tether distributor during deployment.

The tether material used in this paper is Dyneema, and it is uniformly and tightly wound around the reel. It passes through the tether distributor and the tether feeder before connecting to the ejection and docking mechanism. The tether in this experiment is also tested in a simulated space environment, confirming its feasibility.

Finally, a planar air-bearing experiment is executed to demonstrate the deployment and retrieval of a two-body tethered satellite system. The experimental results validate the feasibility of the proposed mechanism based on the designed optimal trajectories for deployments and retrievals.

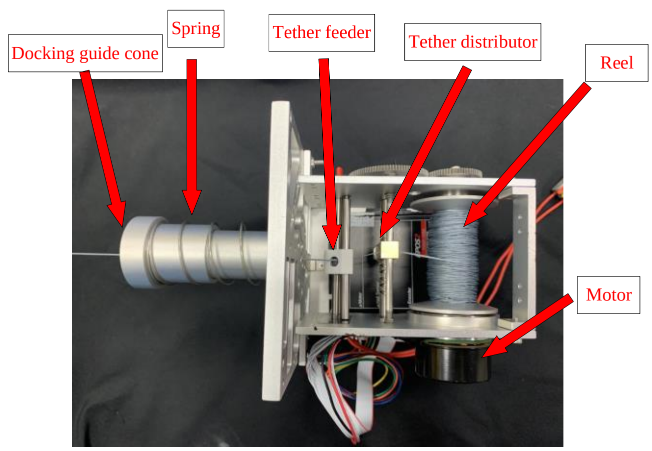

Figure 1. A mechanism for ground experiments

References

[1] Dobrowolny, M., Stone, N.H., " A technical overview of TSS-1: The first Tethered-Satellite system mission ", Il Nuovo Cimento C, Vol. 17, pp. 1 - 12, 1994, doi: 10.1007/BF02506678
[2] Kruijff, M., van der Heide, E., " Qualification and in-flight demonstration of a European tether deployment system on YES2 ", Acta Astronautica, Vol. 64, pp. 882 - 905, 2009, doi: 10.1016/j.actaastro.2008.10.014.
[3] Luo C., Wen H., and Jin D., " Deployment of flexible space tether system with satellite attitude stabilization ", Acta Astronautica, Vol. 160, pp. 240 - 250, 2019, doi: 10.1016/j.actaastro.2019.04.036.

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7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

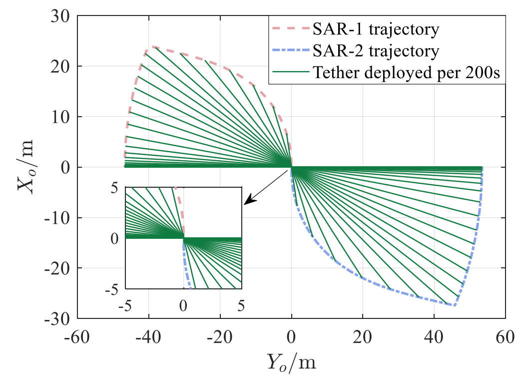
Along-Track Deployment Control of Space Tether System for SAR-GMTI Mission

Linxiao Li[1], Aijun Li[1], Hongshi Lu[1], Changqing Wang[1]
1 School of Automation, Northwestern Polytechnical University, Xi'an 710129, China, luhs@nwpu.edu.cn

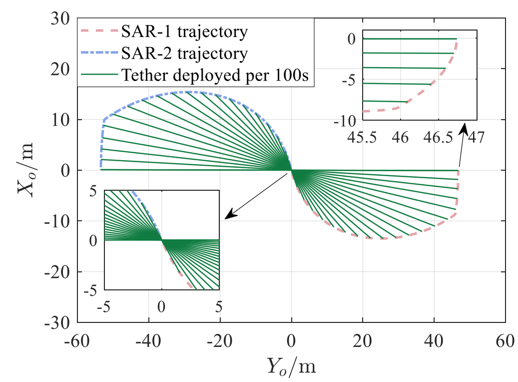
Conference Topic: Tethered Satellite Constellations for Global Communication or Remote Sensing

Global, 24/7, and all-weather synthetic aperture radars (SARs) are ideal platforms for ground-moving target indication (GMTI) missions, and technology with distributed spaceborne SARs is a common solution to achieve this goal[1]. Compared to conventional untethered structure, spaceborne SARs tethered with each other avoids the complicated flying around maneuvers and their resulting periodic variations in interferometric baselines, providing stable interferometric baselines without additional fuel consumption of flying around[2]. Nevertheless, compared to conventional missions, GMTI missions put new requirements to the deployment process of space tether systems (STSs): As such missions explicitly require the stabilization of the interferometric baseline at the along-track position, tethers are required to deploy to the special positions with in-plane angle of ±90 deg, which are unstable relative to the local vertical[3]. Such an unusual requirement puts a new challenge to tether deployment control, which has not been studied adequately yet.

Focused on the aforementioned issue, this paper mainly studies the STS deployment process to the along-track position of a GMTI mission. Firstly, the properties of the STS at the along-track position are analyzed based on the Lagrangian model. Then, the observation principle of the GMTI mission is employed to define a synthetic criterion of measurement error for tether deployment. Third, two deployment strategies are proposed, and corresponding trajectories are generated by considering two scenarios of deploying to the positions of -90 deg and 90 deg respectively. The first scenario ensures a stable deployment with a longer operation time, and the second scenario ensures a quick deployment. It was also found in this paper that, to achieve an along-track deployment, the STS requires thrust assistance when the initial in-plane angle is 0 deg. On the other hand, when the initial in-plane angle falls within the range of over 90 deg or under -90 deg, it becomes feasible to achieve deployments without thrust by searching for the optimal initial state. In the end, an adaptive closed-loop controller is designed using the backstepping method to track the reference trajectories. Simulations demonstrate that the proposed adaptive controller can quickly track the desired trajectories under initial state errors and environmental disturbances. Under both deployment control strategies, the system can successfully attain the desired position with a measurement error criterion of less than 10^{-8}. This study presents a theoretical foundation for utilizing STS in the area of SAR Earth observation.



(a) Control strategy I (stable deployment)



(b) Control strategy II (quick deployment)

Figure 1. Relative motion of STS during two deployment processes

References

[1] Manfred, Z., Alberto, M., Irena, H., et al. "TanDEM-X: 10 years of formation flying bistatic SAR interferometry ", IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, Vol. 14(02), pp. 3346 - 3565, 2021.

[2] Jinxiu, Z. and Zhigang, Z. "Deployment research of multi-tethered InSAR system for GMTI mission ". 2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Beijing, China, pp. 4792 - 4795, 2016.

[3] Shumin, C., Aijun, L., Changqing, W., et al. "Adaptive sliding mode control for deployment of electrodynamic tether via limited tension and current ", Acta Astrodynamica, Vol. 177, pp. 842 - 852, 2020.

THE SEVENTH INTERNATIONAL CONFERENCE ON TETHERS IN SPACE

(June 4th, 2024)

ABSTRACT

Session 7 - Space Tether

Chair: Dr. Mani Kakavand

- **Title:** A Concept Design of Novel Dyson-Harrop CubeSat for Harvesting Energy from Solar Wind (2024088)
- **Title:** Finite Element Model-Based Computational Control and State Estimation for Flexible Space Tether System (2024084)
- **Title:** Space Tether Research at the University of Stuttgart (2024079)
- **Title:** De-Spin and Reorientation Control of Asteroid by Tethered Spacecraft (2024068)
- **Title:** Modeling and Control of Orbital Perturbation Torques and Mass Distribution Impact on Libration Dynamics of Tethered Systems: A Case Study of a 12U Tethered CubeSat System with a 100 m, Non-conductive, Rigid Space Tether on Sun-Synchronous Orbit (2024043)
- **Title:** Hardware in the Loop Validation of the Attitude Determination and Control System of a Deorbit Device Equipped with an Electrodynamic Tether (2024039)
- **Title:** Bare Photovoltaic Tether Characteristics for ISS Reboost (2024044)

Paper No: 2024088
7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

A Concept Design of Novel Dyson-Harrop CubeSat for Harvesting Energy from Solar Wind

Fuzhen Yao[1], Zheng H. Zhu[2]
1 York University, Toronto, Canada, yaofz@yorku.ca
2 York University, Toronto, Canada, gzhu@yorku.ca

Conference Topic: Tether Propulsion and Energy Generation (Tether Power Generation and Energy Harvesting)

This paper unveils a concept design for a novel Dyson-Harrop CubeSat for harvesting energy from solar wind. By capitalizing on the photoelectric effect, the proposed CubeSat establishes a potential difference, achieving consistent current by capturing free electrons prevalent in the solar wind. Impressively, the projected energy yield from a singular cubic satellite can satisfy the demands of 200 households or 35 international space stations. To optimize the transmission of this green energy, we conceptualize a strategically placed solar constellation network, supplemented by earthbound receiving infrastructure. Through comprehensive evaluation, the levelized cost of electricity (LCOE) of this setup emerges favorably against terrestrial power solutions, asserting its economic and operational viability.

In order to promote the industrial application of the Dyson-Harrop satellite, a redesign of the CubeSat system has been carried out. The structure of the CubeSat adheres to strict industry standards and offers several significant advantages: 1) CubeSats enable the large-scale deployment of highly maneuverable functional units, facilitating the efficient transportation of multiple satellites in a single rocket launch; 2) Using CubeSats can save costs associated with satellite design, production, and launch; 3) The convenient replacement of units within the system accelerates the iteration process; 4) Mature post-mission disposal mechanisms mitigate the risk of generating space debris.

As the primary unit in the solar wind power system, the CubeSat possesses the ability to convert kinetic energy from the solar wind into electric energy. The energy is then directed to the desired location through a microwave power transmission system. Fig.1 provides a depiction of the solar wind power CubeSat. To remain stationary relative to the Earth, the CubeSat needs to be positioned at a distance of 1 astronomical unit (AU) from the Sun, which corresponds to its orbital radius. The CubeSat consists of a 3U main satellite equipped with a microwave emitting device, a capacitor-style receiver, a ring-shaped copper sail, a closed-loop rectangular circuit, and an anti-static device. The operational procedure of the CubeSat is as follows:

1) The high-speed moving plasma composed of electrons, protons, and positive ions carried by the solar wind is directed parallel to the CubeSat.

2) The main satellite energizes a closed-loop rectangular circuit, generating a magnetic field that attracts electrons from the solar wind to the receiver.

3) The photons emitted from the Sun collide with electrons on the sail, causing the electrons to jump off the edge of the sail and fly towards the Sun. Under the influence of a magnetic field, they move away from the sail and accumulate a positive potential.

4) The microwave power transmission system connects the sail with the positive potential and the receiver surface with the negative potential, causing electrons to move continuously from receiver to sail. The resulting stable current carries energy to the microwave.

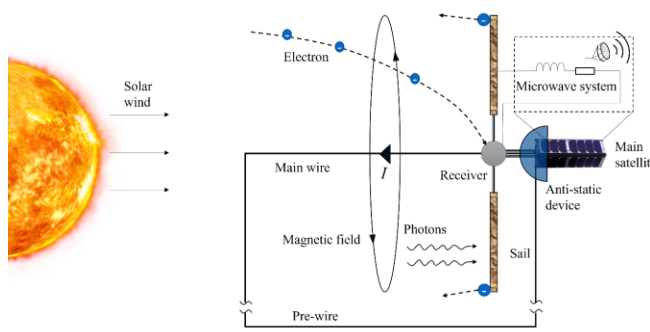


Figure 1. Basic architecture of the novel Dyson-Harrop CubeSat concept

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Finite Element Model-Based Computational Control and State Estimation for Flexible Space Tether System

Qi Zhang[1],*, Zheng H. Zhu[2],*
[1]Department of Earth and Space Science and Engineering, York University, Toronto, Canada
[2]Department of Mechanical Engineering, York University, Toronto, Canada
*qi95@yorku.ca, *gzhu@yorku.ca

Conference Topic: Fundamental Research on Space Tethers

Tethered space system (TSS) as shown in Fig. 1 typically comprises two or more spacecraft connected by a flexible tether(s). It is a promising technology for diverse space missions including orbital maneuvering [1]-[3], artificial gravity [4][5], spacecraft formation flying [6][7], target capture [8]-[10], target detumbling [11]- [13], and space elevators [14]-[17]. To ensure the success of the missions, significant efforts have been dedicated to addressing critical tasks related to TSS due to its complex dynamic behavior arising from intricate space environments, strong system nonlinearity, tether flexibility, and dumbbell-like stability [18]. These complexities present significant control challenges, particularly concerning tether profile sensing, underactuated behavior, and computational efficiency, which are critical for space tether missions.

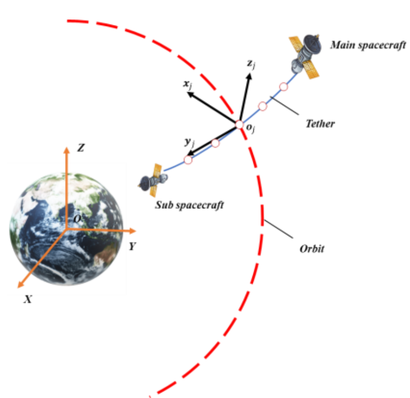

Fig. 1. The schematic diagram of the TSS model

Motivated by this, this paper presents a comprehensive computational control framework specifically designed for the management of flexible space tether systems, with a particular focus on configurations where actuation mechanisms are limited to spacecraft positioned at the end of the tether. The nodal position finite element method is utilized to construct a high-fidelity dynamic model that accurately reflects the intricate behaviors characteristic of flexible systems. Confronting the obstacle of direct state measurement in such systems, we propose an innovative robust finite element state estimation strategy. This strategy synergizes measurements from tether endpoints, distributed fiber optic strain data along the tether, and a virtual sensor model, thereby facilitating precise system state estimation under challenging conditions. A novel inverse nodal position finite element method is developed to convert the distributed fiber optic strain measurement along the tether into the position estimates of internal nodes in the finite element model of the tether in the spatial domain. The model-based virtual sensor was established to estimate the velocities of internal nodes by combining the position and velocity measurements at the satellites and the internal nodal positions.

Building on these advancements, we present a high-fidelity model-based computational control framework based on optimal control theory. The initial optimal control problem is restructured into a two-point boundary value problem using Pontryagin's principle. Numerical control input is then procured by solving this transformed problem, and the re-computation approach is implemented to enable feedback control of the system. To validate our proposed estimator and control framework, we conduct numerical simulations on a tethered satellite system in orbit. The results underscore the framework's efficacy, demonstrating its potential applicability across a broad spectrum of flexible body systems.

References

[1] Bekey, I. (1983). Tethers open new space options. Astronautics Aeronautics, 21, 32-40.

[2] Kyroudis, G. A., & Conway, B. A. (1988). Advantages of tether release of satellites from elliptic orbits. Journal of Guidance, Control, and Dynamics, 11(5), 441-448.

[3] Tragesser, S. G., & San, H. (2003). Orbital maneuvering with electrodynamic tethers. Journal of Guidance, Control, and Dynamics, 26(5), 805-810.

[4] Martin, K. M., Landau, D. F., & Longuski, J. M. (2016). Method to maintain artificial gravity during transfer maneuvers for tethered spacecraft. Acta Astronautica, 120, 138-153.

[5] Gou, X. W., Li, A. J., Tian, H. C., Wang, C. Q., & Lu, H. S. (2018). Overload control of artificial gravity facility using spinning tether system for high eccentricity transfer orbits. Acta Astronautica, 147, 383-392.

[6] Zhang, Z., Yang, H., Jiang, B., Cocquempot, V., & Cheng, Y. (2017). Decentralised fault - tolerant control of tethered spacecraft formation: an interconnected system approach. IET Control Theory & Applications, 11(17), 3047-3055.

[7] Liu, C., Wang, W., Kang, J., & Zhu, Z. H. (2023). Spin deployment of Hub-Spoke tethered satellite formation with sliding mode tether tension control. Advances in Space Research, 71(5), 2509-2520.

[8] Zhai, G., Qiu, Y., Liang, B., & Li, C. (2009). On-orbit capture with flexible tether–net system. Acta Astronautica, 65(5-6), 613-623.

[9] Zhai, G., Zhang, J. R., & Yao, Z. (2013). Circular Orbit Target Capture Using Space Tether-Net System. Mathematical Problems in Engineering, 2013, 1-11.

[10] Huang, P., Wang, D., Meng, Z., Zhang, F., & Liu, Z. (2016). Impact dynamic modeling and adaptive target capturing control for tethered space robots with uncertainties. IEEE/ASME Transactions on Mechatronics, 21(5), 2260-2271.

[11] Kang, J., & Zhu, Z. H. (2018). De-spin of massive rotating space object by tethered space tug. Journal of Guidance, Control, and Dynamics, 41(11), 2463-2469.

[12] Kang, J., & Zhu, Z. H. (2019). Dynamics and control of de-spinning giant asteroids by small tethered spacecraft. Aerospace Science and Technology, 94, 105394.

[13] Wen, H., & Jin, D. (2019). De-spinning of tethered space target via partially invariable deployment with tension control. Nonlinear Dynamics, 96, 637-645.

[14] Edwards, B. C., & Westling, E. A. (2003). The space elevator. BC Edwards.

[15] Yamagiwa, Y., Nohmi, M., Aoki, Y., Momonoi, Y., Nanba, H., Aiga, M., . & Watahiki, M. (2017). Space experiments on basic technologies for a space elevator using microsatellites. Acta Astronautica, 138, 570-578.

[16] Shi, G., Zhu, Z., & Zhu, Z. H. (2018). Stable orbital transfer of partial space elevator by tether deployment and retrieval. Acta Astronautica, 152, 624-629.

[17] Li, G., & Zhu, Z. H. (2019). On libration suppression of partial space elevator with a moving climber. Nonlinear Dynamics, 97, 2107-2125.

[18] Luo, C., Wen, H., & Jin, D. (2019). Deployment of flexible space tether system with satellite attitude stabilization. Acta astronautica, 160, 240-250.

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Space Tether Research at the University of Stuttgart

K. Waizenegger[1,2], M. Kanzow[1], M. Gewehr[1], M. Lengowski[1], S. Klinkner[1]
[1] University of Stuttgart's Institute of Space Systems, Stuttgart, Germany
[2] kevin.waizenegger@irs.uni-stuttgart.de

Space Tether Technology Development and Experimental Studies

Space tether activities at the University of Stuttgart date back to the late 1990s. First research projects investigated tether-assisted re-entry of payload return capsules from space stations. This research concluded in 2005 with optimisation studies and mission concepts for payload retrieval from the International Space Station. [1]

After a hiatus, tether research was resumed within the last decade at the University of Stuttgart's Institute of Space Systems, this time focussing on the application of tethered planetary exploration rovers. Recently, tether research activities at the University of Stuttgart have expanded to in-orbit applications, such as tethered satellite systems (TSS) and Momentum Exchange Tether (MET) missions.

Research on tethered rovers for planetary exploration is based on the Nanokhod, a Micro-Rover for scientific exploration in extreme environments like the surface of Mercury [2], developed by a consortium under the lead of the company von Hoerner & Sulger GmbH (vH&S). Since 2015 the University of Stuttgart has conducted research in cooperation with vH&S, adapting the Nanokhod design for lunar surface exploration (see Figure *1* left). Starting in 2019, the University of Stuttgart and vH&S conducted a project to improve the Nanokhod Tether Mechanism. A novel miniaturised and sealed spooling and recoil mechanism for an ESCC-conform coaxial cable tether was developed. The enhanced mechanism and tether facilitate the transfer of power and data over a maximum distance of 100 meters between the rover and the lander (see Figure *1* right). [3]

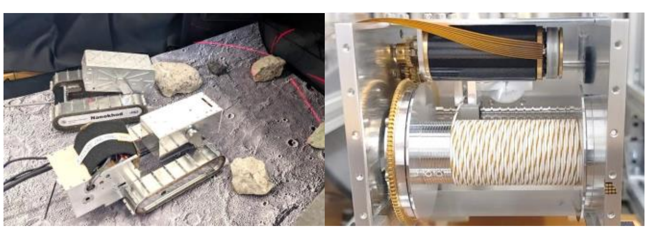

Figure 1. Left: Nanokhod Laboratory (front) and Mechanical Model (back) on a test demonstration
Right: Nanokhod Tether Mechanism (right)

Considering the advancements of the tether mechanism, allowing active recoil and deployment of the tether, several comprehensive design studies were undertaken for lunar exploration missions employing its potential. Graduate students were included in these activities in the scope of the hands-on interdisciplinary educational course "Development of an Exploration Rover System". [4]
Additional studies undertaken at the University of Stuttgart also show the potential of a small swarm of tethered Nanokhod micro rovers to investigate the lunar surface plasma and dust particle levitation processes, local space weather conditions as well as surface-bound and depth-dependent subsurface electrostatic properties for future lunar surface exploration.

Inherent limited resources in space missions require robust and highly-integrated technological solutions. With miniaturised tethered rover systems like the Nanokhod, tether diameters of roughly 1 to 2 mm are required to achieve practical operational distances. Miniaturised wire-based tethers with these dimensions face significant limitations in data rates and power transfer, especially in lengths beyond several 100 meters. This led to the ongoing development of a miniaturised fibre and conductor hybrid tether. The aim of this research is to investigate and enable an interference-free, decoupled and high-performance communication and power link, crucial for dynamic and harsh lunar environments. The results on hybrid tethers can be applied to a broader range of space tether applications as well.

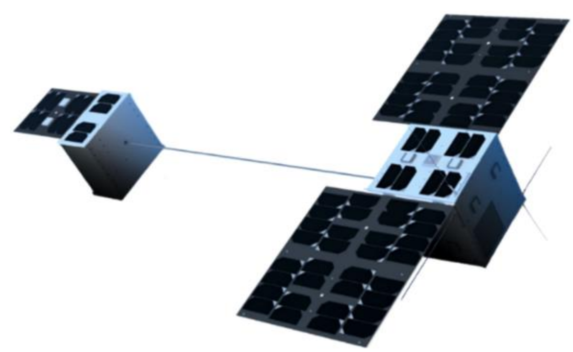

Figure 2. Tethered CubeSat mission developed in the master's course "Small Satellite Project"

Based on the experience of the planetary tether applications, the research at the University of Stuttgart was expanded to tethered satellite systems (TSS) in 2022. First, in-depth studies on tethered CubeSat missions were developed as part of the master's course "Small Satellite Project". Two student teams conducted a feasibility study for CubeSat missions conducting atmospheric in-situ research and rendezvousing with space debris, utilising electrodynamic tethers for orbital changes. In parallel to these studies, two student teams developed the detection and tracking system for tethered objects in a distance of 100 m on a breadboard level for these missions in the scope of the "Rover System Technology" master's module. [5]

Subsystem development necessary for such missions is currently in progress. This includes the modelling of a ridged tethered CubeSat system and the corresponding design of AOCS algorithms, design modification of the Nanokhod Tether Mechanism for on-orbit application and the development of a docking mechanism for tethered CubeSats.

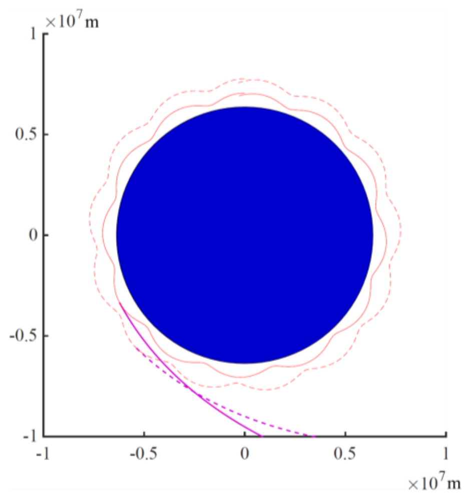

Figure 3. Orbital path of a payload attached to a rotating MET in orange in two different orbits (solid/dashed) and in the respective lunar transfer orbits in purple after being tossed

Concurrently, a third tether application research area was established in 2022. Within a master thesis, a concept study of a Momentum Exchange Tether (MET) mission was conducted. A simulation tool was developed to calculate the behaviour of the rotating tether in Earth's orbit and to determine the orbits of payloads after being collected and tossed by the MET. Figure 3 shows the simulated orbital path of a payload attached to a MET in two different orbits around Earth and the resulting two lunar transfer orbits after being tossed.
Based on this simulation tool, a feasible configuration was developed, capable of serving as infrastructure to support regular lunar missions with payloads of up 30 t. Various technological and operational challenges were identified and are now the focus of ongoing research at the University of Stuttgart. [6]

This paper aims to present and detail the recent space tether research activities at the University of Stuttgart and their objectives and results, covering tethered planetary exploration rovers, tethered satellite systems as well as momentum exchange tether missions.

References

[1] Zimmermann, F., Schöttle, U. M., Messerschmid, E. "Optimization of the tether-assisted return mission of a guided re-entry capsule", Aerospace Science and Technology, Vol. 9, Is. 8, pp. 713 – 721, 2005, doi: 10.1016/j.ast.2005.09.002

[2] Lee, C.G.–Y., Klinkner, S., Hlawatsch, W., Wagner, C., Schreyer A.–M., Röser, H.–P., Schaefer, J., Schiele, A., Romstedt, J., "Mercury Nanokhod Rover – Hardware Realisation and Testing", ASTRA 2006, Noordwijk, Nov. 2006

[3] Gewehr, M., Schneider, A., Dalcolmo, J., Klinkner, S., "Design and Testing of a Novel Miniaturised Sealed Tether-Recoil Mechanism for the Nanokhod Microrover", ESMATS, 2021

[4] Nitz, M., and Klinkner, S., "Evaluation of an Interdisciplinary Postgraduate Education Program on Space Robotics and Planetary Exploration Technologies within the Institute of Space Systems at the University of Stuttgart", Proceedings of the 70th International Astronautical Congress (IAC), Washington D.C., USA, 2019

[5] Gewehr, M., Kanzow, M., Blank, S., Bonidis, A., Ruedorffer, P., Friedrich, D., Kobiak, D., Kocic, I., Komposch, M., Largent, P., Lauer, L., Lehnert, P., Mayer, C., Nevola, M., Pentke, N., Pfaff, J., Preis, M., Schneider, M., Siedler, J., (…), Klinkner, S., "GET Space - Growth of Education and Technology for Space: An Interdisciplinary Education Project on Tethered CubeSat Missions and Robotic Space Technologies at the University of Stuttgart", Proceedings of the 74th International Astronautical Congress (IAC), Baku, Azerbaijan, 2023

[6] Waizenegger, K., "Concept Study of a Skyhook System for Exploration Missions", unpublished master's thesis, University of Stuttgart, Stuttgart, Germany, 2023

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De-spin and Reorientation Control of Asteroid by Tethered Spacecraft

Junjie Kang[1], Changqing Wang[2], Aijun Li[2], Zheng Hong Zhu[1]
1 York University, Toronto, Canada (kjj@yorku.ca, gzhu@yorku.ca)
2 Northwestern Polytechnical University, Xi'an, China (wangcq@nwpu.edu.cn, liaijun@nwpu.edu.cn)

Conference Topic: Planetary Exploration and Utilization

This study investigates the de-spin and reorientation control of a rotating asteroid utilizing a small tethered spacecraft during the post-capture phase, particularly when captured by a flexible net/bag. Unlike rigid capture approaches involving space robot arm/gripper systems, applying active control directly to the asteroid is often challenging. Consequently, our study proposes a promising "passive" control strategy achieved by actively adjusting the tethered spacecraft, providing an effective approach for the de-spin and reorientation control of rotating asteroids.

First, we derive the dynamic equations of the system using the Lagrange formulation. Subsequently, we determine the attainable equilibrium configurations of the tethered system based on the governed equations. Following this, a coordinate transformation is applied to approximately feedback linearize the system. Next, the de-spin/reorientation controllers are designed to stabilize the system at the attainable equilibria. The asymptotic stability of this underactuated tethered system is strictly proven with help of the Lyapunov techniques and the Barbalat's Lemma. Numerical simulations are then conducted to demonstrate the effectiveness and performance of the proposed de-spin and reorientation controller for de-spin and reorientation.

Followings are some simulation results.

Case-1 De-spin under different thrusters.

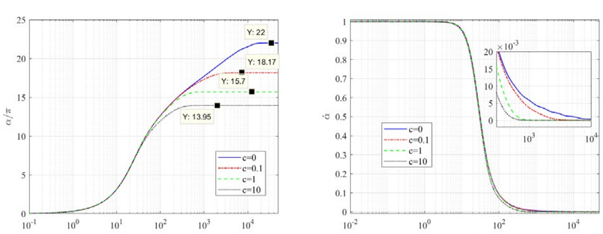

Figure 1. Rotation angle and angle rate of Asteroid

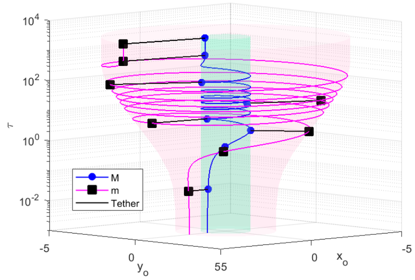

Figure 2. Configuration of tethered system in orbital frame

Case-2 De-spin under different tether lengths.

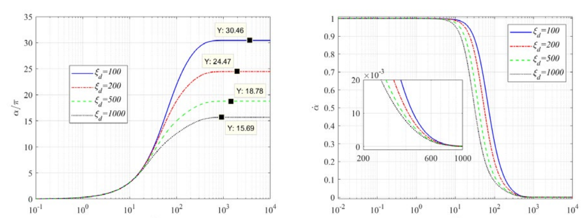

Figure 3. Rotation angle and angle rate of Asteroid

Case-3 Reorientation control.

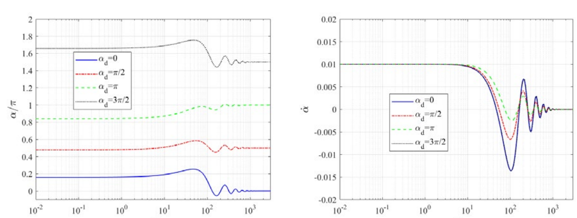

Figure 4. Rotation angle and angle rate of Asteroid

Observed from numerical studies, the proposed de-spin/reorientation controller proves effective under different operational conditions.

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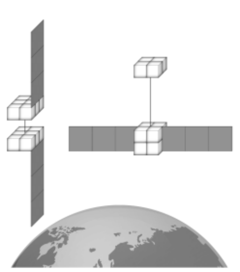
Modeling and Control of Orbital Perturbation Torques and Mass Distribution Impact on Libration Dynamics of Tethered Systems: A Case Study of a 12U Tethered CubeSat System with a 100 m, Non-conductive, Rigid Space Tether on Sun-Synchronous Orbit

Bahareh Vossoughi[1], Marlin Kanzow[2]
[1]RWTH Aachen University, Faculty of Mechanical Engineering, Aachen, Germany, bahareh.vossoughi@rwth-aachen.de
[2]University of Stuttgart, Institute of Space Systems, Stuttgart, Germany, kanzowm@irs.uni-stuttgart.de

Conference Topic: Fundamental Research on Space Tethers, Mathematical Modeling of Space Tethers, Dynamics, Controls.

CubeSats are increasingly captivating the interest of academia and researchers alike. Meanwhile, Tethered CubeSat systems offer a cost-effective avenue for exploring and use of the distinctive features of tethered systems such as momentum exchange of the end satellites and gravity gradient stabilization of the system. While it has been established that long tethered systems (several kilometers long) exhibit enhanced gravity gradient stabilization [1], the same cannot be unequivocally affirmed for shorter tethered configurations (several meters to several hundred meters). Particularly, in the presence of perturbing torques, in highly inclined and eccentric orbits, Tethered Satellite Systems (TSS) stability is challenged. This paper explores the impact of key orbital perturbation torques and the mass distribution on the libration dynamics of a tethered CubeSat system throughout its deployment, station-keeping, and retrieval phases. A 12 standard unit (12U) CubeSat in stowed configuration is analyzed for this case study. Two deployed configurations of the system with different inertias namely, the symmetrical 6U-6U and the asymmetrical 8U-4U are investigated. The end masses, which adhere to the CubeSat Design Specification (CDS), are connected by a tether with a maximum length of 100 m. A maximum tether release/retrieve rate of 15 m/h from/to a mechanism mounted on the satellite closer to Earth, is assumed for the system. The perturbing effects of Earth's oblateness, atmospheric drag, solar radiation pressure, and lunisolar gravitation are investigated for the defined operational phases. In mathematical modeling based on Lagrangian formalism, and simulation of dynamic behavior, the tether is presumed to be rigid, massive, and extendable. The satellites are simplified as lumped masses at both ends of the tether. The system's translational and rotational dynamics are decoupled, with the overall center of mass assumed to follow an unperturbed Keplerian Sun-Synchronous Orbit (SSO) at altitudes ranging from 400 to 600 km. Moreover, the reliability of a control strategy based on Lyapunov's direct method is explored for tension control augmented with actuation. In contrast to previous studies applying this method to TSS control, the perturbation torques, tether mass, and system inertia are not neglected. In this study, the energy-based Lyapunov function is derived from the system's Hamiltonian [2].

Table 1. Tethered CubeSat System Configuration Sketch and Properties



Properties	6U-6U symmetrical	8U-4U asymmetrical
Total mass	24.4 kg	24.4 kg
Effective area	0.21, 0.21 m^2	0.28, 0.02 m^2
Tether mass	0.4 kg	0.4 kg
Tether diameter	0.002 m	0.002 m
Max. tether length	100 m	100 m
Max. tether rate	15 m/h	15 m/h

Simulation results reveal several noteworthy findings: Large orbit eccentricity (e) has a perturbing effect on the libration of the tethered satellite system even in the absence of perturbations and regardless of system's configuration. With values as large as e = 0.5, the libration angle of the system in the orbital plane exceeds values of 220°. A comparison of the symmetrical and asymmetrical configurations confirms that the symmetrical system experiences smaller in-plane and out-of-plane torques about its center of mass. Nevertheless, tether tension magnitudes and variations are larger than the asymmetrical system. Both systems exhibit larger in-plane oscillations compared to out-of-plane angles. The space environment-induced perturbation torques remain periodic and relatively constant over time. Hence, the variations of the libration angles during the station-keeping phase also remain periodic. However, the simulation results indicate that the eclipse passages have a negative effect on the out-of-plane libration of the 8U-4U system, leading to large out-of-plane oscillation amplitudes, exceeding that of the in-plane angles over time.

The results of this study reinforce the observation of a relatively stable dynamic behavior during the deployment phase and the inherently chaotic nature of the retrieval phase with large oscillation amplitudes for libration angles and the tether tension, a characteristic previously explored in existing studies. The employed tension control strategy closely relates to tether release/retrieve rate control and effectively dampens the oscillations and angle rates during the retrieval phase while improving the deployment behavior. However, the effectiveness of the tension control is constrained by the tether's limited tension which nears zero at the end of retrieval. The demanded external actuation torques alongside the tension control are calculated to be 1-2 mNm for the deployment phase, and up to 15 mNm for the retrieval phase.

References:

[1] Yi Chen et al. "History of the tether concept and tether missions: a review". In: *InternationalScholarly Research Notices* (2013).
[2] Francisco JT Salazar and Antonio BA Prado. "Controlling Tether Deployment and Retrieval by Lyapunov Approach Involving Quasiperiodic and Chaotic Motions" (2022).

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Hardware in the Loop Validation of the Attitude Determination and Control System of a Deorbit Device in the Tether Deployment Preparation Phase

G. Sharifi[1], S. Garcia-Gonzalez[2], D.Cruces[3], G. Sanchez-Arriaga[4]
1 Universidad Carlos III de Madrid, Aerospace Department, Madrid, Spain, gsharifi@ing.uc3m.es
2 Sener Aeroespacial, Madrid, Spain, sergio.garcia@aeroespacial.sener
3 Sener Aeroespacial, Madrid, Spain, daniel.cruces@aeroespacial.sener
4 Universidad Carlos III de Madrid, Aerospace Department, Madrid, Spain, gonsanch@ing.uc3m.es

Conference Topic: Space Tether Technology Development and Experimental Studies- Subsystem Technologies to Enable Space Tether Missions

Hardware-in-the-loop (HIL) testing is an essential procedure during the development and validation of Attitude Determination and Control Subsystem (ADCS) for satellites. The HIL setup involves a close-loop system with hardware and software. It mimics the space environment and the actual ADCS, allowing for the comprehensive evaluation of ADCS algorithms, sensors, and actuators in a controlled and repeatable environment. Among the different testbeds that can be used, HIL setups based on air bearing offer a dynamically representative environment at a low cost [1]. In the case of space tethers, the ADCS plays a crucial role in the tether deployment preparation phase. For non-spinning tethers, the ADCS should ensure that the deployment is expected to take place the tether lies along the local vertical at the end of the deployment phase [2].

In a recent work [3], an architecture for the ADCS subsystem of a deorbit device in the tether deployment preparation phase was proposed, together with estimation algorithms and control laws. The attitude determination and control algorithms for this phase encompass two sub-modes: detumbling and coarse nadir pointing. They use four sensors (gyroscope, magnetometer, coarse sun sensors, and GNSS) and a 3-axis magnetorquer as actuators for attitude control. Additionally, a multiplicative Extended Kalman Filter (EKF) was used for attitude determination, along with the construction of two independent control laws for the detumbling of the deorbit device and subsequent pointing stabilization [3]. Numerical simulations were conducted to study the performance of the proposed approach. This paper aims to transition from simulation to experimental validation, providing a comprehensive assessment of the algorithms' performance combined with a HIL. The proposed HIL test consists of two essential steps. The initial step focuses on validating the attitude estimation by employing the developed EKF algorithm alongside real sensors (gyroscope, magnetometer, sun sensors). The experimental setup uses a Free-floating Air-Bearing Table (FABT), real sensors, and an attitude heading reference system to compare the results. The accuracy of the EKF is assessed across different scenarios, including eclipse and daytime lighting, and varying angular velocities. Additionally, the EKF's robustness is tested by substituting redundant sensors for primary ones, exploring its adaptability and reliability with alternative sensor data. This evaluation is conducted in both static and dynamic conditions, offering insights into the algorithm's performance. In the second step, a comprehensive validation of control and attitude estimation is undertaken by integrating magnetic torquers and cold gas thrusters with the attitude algorithm, employing a FABT. The actuator-level evaluation focuses on analyzing actuator performance, considering factors like frequency of operation and execution of commands from the on-board computer. At the control level, the test includes mode switching, a detumbling phase to reduce angular velocity, and pointing maneuvers to rotate the modules toward a desired point. Additionally, we investigate the scenario for updating algorithm parameters from the ground station during the test, thus emulating the process occurring in the future mission.

References

[1]. Tomasz Rybus, Karol Seweryn, Planar air-bearing microgravity simulators: Review of applications, existing solutions and design parameters, Acta Astronautica, Volume 120,2016,Pages 239-259,ISSN 0094-5765,

[2]. Sarego, G., Olivieri, L., Valmorbida, A., Brunello, A., Lorenzini, E.C., Tarabini Castellani, L., Urgoiti, E., Ortega, A., Borderes-Motta, G., Sánchez-Arriaga, G. (2021), Deployment requirements for deorbiting electrodynamic tether technology, CEAS Space Journal 13(A6). 10.1007/s12567-021-00349-5

[3]. Garcia-Gonzalez, Sergio & Sanchez-Arriaga, Gonzalo. (2022). Attitude determination and control for the deployment preparation phase of a space tether mission. Acta Astronautica. 193. 10.1016/j.actaastro.2022.01.01

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Bare Photovoltaic Tether characteristics for ISS reboost

G. Anese[1], A. Brunello[2], G. Colombatti[3], A. Del Pino[4], E.C. Lorenzini[5]

1 CISAS "G.Colombo", University of Padua, Padua, Italy, giovanni.anese@phd.unipd.it
2 CISAS "G.Colombo", University of Padua, Padua, Italy, alice.brunello@phd.unipd.it
3 CISAS "G.Colombo" and Dept. of Industrial Engineering, University of Padua, Padua, Italy, giacomo.colombatti@unipd.it
4 Aerospace Engineering Department, Universidad Carlos III de Madrid, Madrid, Spain, adelpino@pa.uc3m.es
5 CISAS "G.Colombo" and Department of Industrial Engineering, University of Padua, Padua, Italy, enrico.lorenzini@unipd.it

Conference Topic: Tether Propulsion and Energy Generation - Tether Power Generation and Energy Harvesting

The International Space Station (ISS) holds profound significance for humanity as it serves as a pivotal platform for astronauts to conduct and advance research in microgravity, contributing to the development of new exploration technologies. However, due to the atmospheric drag forces, the ISS experiences an average decay rate of around 2 km/month and requires periodic reboosting to maintain its operational altitude of approximately 400 km. Since chemical reboost maneuvers necessitate, every year, around 8 tons of fuel with a huge cost, the exploration of alternative propellant-less technologies becomes imperative. Over the past two decades, numerous studies have explored the feasibility of integrating the ISS with a cost-effective and environmentally sustainable solution, and Electrodynamic tethers (EDTs) may emerge as a potential option for the ISS station-keeping operation without propellant. A notable example is the work described in [1], which demonstrated that a 10-kilometer-long aluminum bare tether could achieve a 90% reduction in propellant usage over a decade. Nevertheless, the viability of this solution is contingent upon an input power, typically ranging from 5-10 kW, which must be drawn from the existing electric power of the ISS. This necessity has consequential implications for the deployment direction that must be downward.

Despite the potential benefits, the integration of a downward-facing tethered system of the ISS encounters stringent regulations, particularly pertaining to the designated corridors for approaching vehicles. To reconcile the demand for power with the prospect of an upward tether deployment, a proposed solution involves the implementation of a Bare-Photovoltaic Tether (BPT) [2]. The BPT extends the partially insulated EDT concept by incorporating a photovoltaic segment composed of thin solar cells to harvest the required input power.

Determining the total tether length and, specifically, the correct fraction of the total tether length to be covered by photovoltaic cells to produce the needed input power, is pivotal in BPT design and system operation. This study proposes the derivation of the required tether dimensions for executing the ISS station-keeping maneuver employing the zig-zag strategy recently presented in [3]. This strategy foresees the alternation of reboost and the natural decay due to drag. The reboost is performed when the ISS falls below a certain altitude H_0, and lasts until the ISS reaches an higher altitude H_F. Then the ISS is left under the action of the atmospheric drag which brings it down to H_0. Both altitudes (H_0 and H_F) are pre-selected during the mission design.

Additionally, once the BPT dimensions are found, the system is evaluated and validated with the use of FLEXSIM [4], a software developed by the University of Padua capable of simulating the dynamics of the ISS during BPT system operation. FLEXSIM can simulate the zig-zag maneuver setting the altitudes at which the BPT has to start and end its operations. The dynamics of the complete system is computed integrating the equations of motion that also consider the Lorentz Force generated by the tether only when the altitude has to be increased. In the decay phase, instead, the BPT is not operative (it is retrieved back), so the Lorentz Force is not produced and hence not included in the equations of motions. Namely, during this phase, only gravity and neutral drag are considered. The maneuver can be simulated for a given time that could be set at the beginning.

The goal of this paper is to showcase the feasibility of implementing the innovative, sustainable, and environmentally friendly concept of BPT technology to benefit the ISS station keeping, creating a fully autonomous system capable of independently generating the necessary input power to carry out that task.

References

[1] R.D.Estes et al., "Bare Tethers for Electrodynamic Spacecraft Propulsion." Journal of Spacecraft and Rockets, Vol. 37, No. 2, 205-211, (2000) URL https://doi.org/ 10.2514/2.3567

[2] M.Tajmar & G.Sanchez-Arriaga, (2021). A bare-photovoltaic tether for consumable-less and autonomous space propulsion and power generation. Acta Astronautica. 180. 350-360. 10.1016/ j.actaastro.2020.12.053.

[3] A.Brunello et al., Optimal design and current control strategies of an electrodynamic tape for ISS station-keeping, conference proceeding of the 74th International Astronautical Conference (IAC2023), Baku, Azerbaijan.

[4] G.Anese et al., Electro-thermal dynamic simulations and results of a deorbiting tethered system, Materials Research Proceedings, Vol. 37, pp 534-537, 2023, doi: https://doi.org/10.21741/9781644902813-117

THE SEVENTH INTERNATIONAL CONFERENCE ON TETHERS IN SPACE

(June 4th, 2024)

ABSTRACT

Session 8 - Space Tether

Chair: Prof. Masahiro Nohmi

- **Title:** The Deployment Mechanism of the E.T.PACK Deorbit System: Functional and Qualification Tests (2024057)
- **Title:** Velocity Observer Design of Space Tether System Using Immersion and Invariance Technique (2024030)
- **Title:** Design of Movement Scheme for Space Station Servicing Satellite (2024022)
- **Title:** Learning-Based Deployment and Retrieval Control of a Spinning Tethered Satellite Formation System (2024069)
- **Title:** Tethered Artificial Gravity Assists for Capture about Binary Asteroids in the Circular Restricted Three-Body Problem (2024091)

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The Deployment Mechanism of the E.T.PACK Deorbit System: functional and qualification tests

A. Brunello[1] , G. Polato[2], A. Valmorbida[3], G. Colombatti[4], S. Chiodini[5], G. Anese[6], E.C. Lorenzini[7]

[1] CISAS "G. Colombo", University of Padova, Italy, alice.brunello.3@studenti.unipd.it
[2] CISAS "G. Colombo", University of Padova, Italy, giulio.polato@studenti.unipd.it
[3] Department of Industrial Engineering (DII) and CISAS "G. Colombo", University of Padova, Italy, andrea.valmborbida@unipd.it
[4] Department of Industrial Engineering (DII) and CISAS "G. Colombo", University of Padova, Italy, giacomo.colombatti@unipd.it
[5] Department of Industrial Engineering (DII and CISAS "G. Colombo" University of Padova, Italy, sebastiano.chiodini@unipd.it
[6] CISAS "Giuseppe Colombo", University of Padova, Italy, giovanni.anese@studenti.unipd.it
[7] Department of Industrial Engineering (DII) and CISAS "G. Colombo", University of Padova, Italy, enrico.lorenzini@unipd.it

Conference Topic: Space tether Technology Development and Experimental Studies – Subsystem Technologies to Enable Space Tether Missions

The space exploration community is currently addressing the pressing challenge of orbital debris through innovative approaches, seeking alternatives to conventional chemical propulsion systems for satellite deorbiting. Electrodynamic Tethers (EDTs) have emerged as a promising solution, offering the capability to generate drag forces without the use of propellant, minimizing the adverse impacts on the space environment. The Horizon 2020 (H2020) Future Emerging Technologies (FET) OPEN Project E.T.PACK was established to advance EDT technology. The project focuses on the research, development, and manufacturing of a Deorbit Device prototype designed for the purpose of deorbiting end-of-life satellites [1][2]. The Deorbit Device prototype consists of two autonomous modules interconnected via a 500-meter-long tape: the Deployment Mechanism Module (DMM), that houses the tape tether and the Deployment Mechanism (DM) responsible for tether extraction, and the Electron Emitter Module (EEM) that accommodates the hollow cathode electron emitter 0.

As a collaborative partner within the E.T.PACK consortium, the University of Padova conducted a series of test campaigns over the course of 2022. These campaigns were strategically focused on deployment tests, which constitute a pivotal phase aimed at refining the tape extraction/guiding assembly and assessing the efficacy of the DM design. The test setup encompassed the fixed spool, the tape guiding assembly, electrical and electronic components, and a power supply. The stationary spool was meticulously crafted using 400 m of Aluminum - the conductive tether segment - and an additional 100 m of PEEK - the inert segment - designed to impart dynamic stability to the system during the deorbiting phase. The fabrication process involved the utilization of a specialized spooling machine. Various tests, including those involving constant velocity, ramp-up, and specific velocity profiles, were conducted on representative tape lengths with the primary objective to scrutinize the condition of each tape section after several meters of extraction, thereby providing valuable insights into the operational capabilities of the DM. The results of these test campaigns demonstrated the DM capacity to deploy tapes with diverse thicknesses and mechanical properties seamlessly. Notably, the attained outcomes culminated in the achievement of a Technology Readiness Level (TRL) falling within the specified range of 4-5 by the conclusion of 2022. This finding contributed to underscore the credibility and potential of the E.T.PACK initiative, leading to the European Commission (EC) endorsement and financial support for the subsequent phase, denoted as E.T.PACK-F, in September 2022. E.T.PACK-F propose to develop a ready-to-fly Deorbit Device (DD), aiming to elevate the TRL to 8, pertaining to the attainment of the Flight Model (FM). Within the scope of the DM development, the Engineering Qualification Model (EQM) has been designed and is currently manufactured leveraging the knowledge acquired from the testing and verification activities conducted on the E.T.PACK prototype in late 2022. End-to-end deployment test following a specific deployment profile - that will bring the system to align with the Local Vertical - covering the full tether length, are planned to be conducted with the aim of refining and optimizing the characteristics of the DM EQM.

This paper endeavors to present the deployment functional tests executed on the DM prototype in late 2022, including the experimental setup and methodology. Additionally, the paper will expound upon the outcomes obtained from the qualification test campaign scheduled for the DM EQM, including the dynamic simulations used to derive the specific deployment velocity profile. The execution of these testing activities paves the way for the preparation and testing of the DM FM and has a pivotal value in assessing the robustness and efficacy of the DM in a real-world operational context.

References

[1] http://www.etpack.eu

[2] G. Sarego et al., Deployment requirements for deorbiting electrodynamic tether technology, CEAS Space J., vol. 13, no. 4, pp. 567–581, Oct. 2021, doi: 10.1007/s12567-021-00349-5.

[3] L. Tarabini Castellani et al., Deorbit kit demonstration mission, Journal of Space Safety Engineering, Volume 9, Issue 2, 2022, Pages 165-173, ISSN 2468-8967, https://doi.org/10.1016/j.jsse.2022.01.004.

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Velocity Observer Design of Space Tether System using Immersion and Invariance technique

Jihang, Yang[1], Yonghe, Xie[1*], Gangqiang, Li[2]

1School of Naval Architecture and Maritime, Zhejiang Ocean University, Zhoushan, China, Xieyh@zjou.edu.cn
2Department of Mechanical, Aerospace and Civil, Engineering School of Engineering, University of Manchester Manchester, UK, Gangqiang.li@manchester.ac.uk

Conference Topic: Mathematical Modeling of the Space Tethers, Dynamics, Controls

In this paper, a velocity observer is proposed for a Space Tether system (STS) using the controlled Port-Hamiltonian framework. The deployment and retrieval process is of interest and has been well studied in Refs. [1–3] . However, it is noticed that not all the states can be directly measured by installed sensors. For example, the libration angle and length of the deployed segment are measured through the onboard sensors, and they should be in real-time [4], but their rate cannot be directly measured. For example, the accurate estimation of the unmeasurable state should be addressed to implement the controller successfully.

Many efforts have been devoted to this direction to address this limitation. The unmeasurable state can be estimated by using the Kalman filter algorithm [5–8]. It is simple and can be easily implemented; however, the defect of this algorithm is apparent. It requires a significant computational source to process the sampling points. Meanwhile, the immersion and invariance (I&I) technique is also explored to estimate the unmeasurable state (libration angle rate) of the libration motion of an electrodynamic tether system [9]. The measurement model of the unmeasurable state can be analytically derived by solving a partial differential equation, and it proved to be estimated accurately [10–12]. The derivation process of the Lyapunov candidate is complex and it depends on the author's experience. In this paper, the I&I technique is applied to design the unmeasurable state estimator. However, different from Wen's work [9], the novelty of this work is converting the velocity observer error system into a generalized Port-controlled Hamiltonian (PCH) framework. An attractive and invariant manifold is defined on an extended PCH framework. Therefore, the problem for observer design is recast as the problem of designing an attractive and invariant manifold inside a PCH framework. Then, the interconnection and damping assignment technique can be directly used to derive an expected Port-Hamiltonian function, which is an ideal Lyapunov function[13]. The attractivity of the proposed manifold is easily achieved by solving a PDE equation [11]. Here, the velocity observer error system is reformed as the PCH form, which retains the damping matrix structure of the PCH system. It can facilitate the definition of disturbance compensation. In this work, the proposed velocity observer for the deployment/retrieval of the STS has an exponential convergence rate.

The proposed velocity observer has been proven to guarantee the exponential convergence of the estimation errors. Then, the performance of the proposed observer for the deployment process of the STS is numerically evaluated via a simulation. This simulation is designed by adapting a dynamic motion process that has a varying velocity. The results are shown in the following Figs 1 and 2. Fig 1 shows time history velocities $\dot{\lambda}$ and $\dot{\theta}$ (solid lines) against the estimated variables $\hat{\dot{\lambda}}$ and $\hat{\dot{\theta}}$. It can be seen that the converging speed of the proposed observer is fast. This phenomenon is also observed in Fig.2, which shows the time histories of the error between the estimator and target.

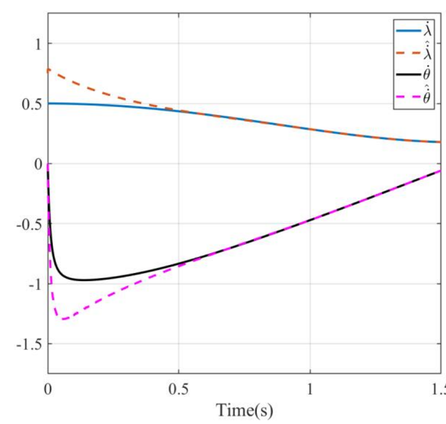

Figure 1. Dimensionless time history of velocities and the observer

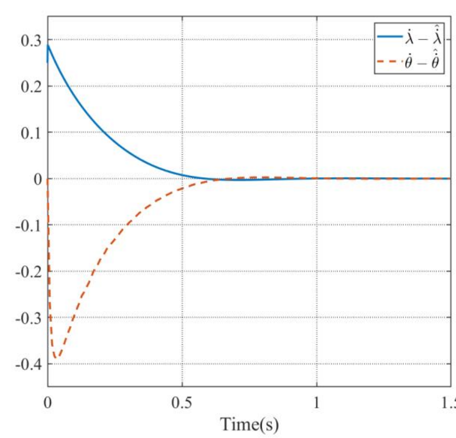

Figure 2. The tracking error of velocities and the observer

References

[1] Vadali, S. R., "Feedback Tether Deployment and Retrieval", Journal of Guidance, Control, and Dynamics, Vol. 14, No. 2, pp. 469–470, 1991, doi: 10.2514/3.20662.

[2] Fujii, H. A., and Kojima, H., "Optimal Trajectory Analysis for Deployment/Retrieval of Tethered Subsatellite Using Metric," Journal of Guidance, Control, and Dynamics, Vol. 26, No. 1, pp. 177–179, 2003, doi: 10.2514/2.5031.

[3] Murugathasan, L., and Zhu, Z. H., "Deployment Control of Tethered Space Systems with Explicit Velocity Constraint and Invariance Principle", Acta Astronautica, Vol. 157, pp. 390–396, 2019, doi: 10.1016/j.actaastro.2019.01.017.

[4] Accardo, D., and Rufino, G., "A Procedure for Three-Dimensional Angular Velocity Determination Using a Star Sensor in High-Rate Rotation Modes", Acta Astronautica, Vol. 48, Nos. 5–12, pp. 311–320, 2001.

[5] T. S. Denney and M. E. Greene, "On State Estimation for an Orbiting Single Tether System", IEEE Transactions on Aerospace and Electronic Systems, Vol. 27, No. 4, pp. 689-695, 1991, doi: 10.1109/7.85043.

[6] Williams, P., "Electrodynamic Tethers Under Forced-Current Variations Part II: Flexible-Tether Estimation and Control", Journal of Spacecraft and Rockets, Vol. 47, No. 2, pp. 320–333, 2010.

[7] Li, G., and Zhu, Z. H., "Estimation of Flexible Space Tether State Based on End Measurement by Finite Element Kalman Filter State Estimator", Advances in Space Research, Vol. 67, No. 10, pp. 3282–3293, 2021, doi: 10.1016/j.asr.2021.01.057.

[8] Tortora, P., Somenzi, L., Iess, L., and Licata, R., "Small Mission Design for Testing In-Orbit an Electrodynamic Tether Deorbiting System", Journal of Spacecraft and Rockets, Vol. 43, No. 4, pp. 883–892, 2006, doi: 10.2514/1.15359.

[9] Wen, H., Zhu, Z. H., Jin, D., and Hu, H., "Exponentially Convergent Velocity Observer for an Electrodynamic Tether in an Elliptical Orbit", Journal of Guidance, Control, and Dynamics, Vol. 39, No. 5, pp. 1113–1118, 2016, doi: 10.2514/1.G001532.

[10] Karagiannis, D., Sassano, M., and Astolfi, A., "Dynamic Scaling and Observer Design with Application to Adaptive Control", Automatica, Vol. 45, No. 12, pp. 2883–2889, 2009, doi: 10.1016/j.automatica.2009.09.013.

[11] Astolfi, A., Ortega, R., and Venkatraman, A., "A Globally Exponentially Convergent Immersion and Invariance Speed Observer for N Degrees of Freedom Mechanical Systems", Proceedings of the 48h IEEE Conference on Decision and Control (CDC) held jointly with 2009 28th Chinese Control Conference, pp. 6508–6513, 2009, doi: 10.1109/CDC.2009.5399984.

[12] Stamnes, Ø. N., Aamo, O. M., and Kaasa, G.-O., "A Constructive Speed Observer Design for General Euler–Lagrange Systems", Automatica, Vol. 47, No. 10, pp. 2233–2238, 2011, doi: 10.1016/j.automatica.2011.08.006.

[13] Ortega, R., van der Schaft, A., Maschke, B., and Escobar, G., "Interconnection and Damping Assignment Passivity-Based Control of Port-Controlled Hamiltonian Systems", Automatica, Vol. 38, No. 4, pp. 585–596, 2002, doi: 10.1016/S0005-1098(01)00278-3.

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Design of Movement Scheme for Space Station Servicing CubeSat

S.Lv[1], R.Xu[2], X.Wang[3], H.Zhang[4], Y.Zhang[5], R.Qi[6], Y.Zhang[7]
1 Beijing Institute of Technology, Beijing, China, lsw_stu@bit.edu.cn
2 Beijing Institute of Technology, Beijing, China, xu_ryang@bit.edu.cn
3 Beijing Institute of Technology, Beijing, China, 1120211584@bit.edu.cn
4 Beijing Institute of Technology, Beijing, China, zhanghj2002@foxmail.com
5 Beijing Institute of Technology, Beijing, China, adel_zy@163.com
6 Beijing Institute of Technology, Beijing, China, qirui@bit.edu.cn
7 Beijing Institute of Technology, Beijing, China, zhangyao@bit.edu.cn

Conference Topic: Other Advanced Tether Concepts

To safely inspect and repair Tiangong Space Station, a short tethered CubeSat is proposed to replace astronauts. The CubeSat uses two tethers which are called umbilical lines[1] to connect its main body, and two probes at both ends which carries out transmission of electricity, information and gas propellant. By getting supplies from the main body, probes are highly simplified sub-satellites while most of systems for a CubeSat are concentrated on the main body. Probes are the working hands of the CubeSat, integrating tools for on-orbit servicing such as cameras, grippers and welding guns, and can move using cold gas thrusters on their body.

During the on-orbit servicing process, the CubeSat needs to frequently move on the surface of the space station. When on the orbit, the propellant is hard to achieve but the electricity is easy to obtain. This paper proposes an Electric-Gas Hybrid (EGH) CubeSat moving mode: Probes move to grab two different handles on the space station. Then one of the umbilical lines is restored and the other is released by electric winches, leading the main body to move. The EGH mode allows the whole CubeSat to move with low propellant consumption, therefore the CubeSat can achieve a longer service life with less external supply.

In order to verify the practicability and potential of the EGH mode proposed above, this paper analyzes the dynamics of the umbilical lines in the process of probes' and the CubeSat's movement in EGH mode, and studies the influence on umbilical lines' transmission capabilities when umbilical lines' shapes change in these processes.

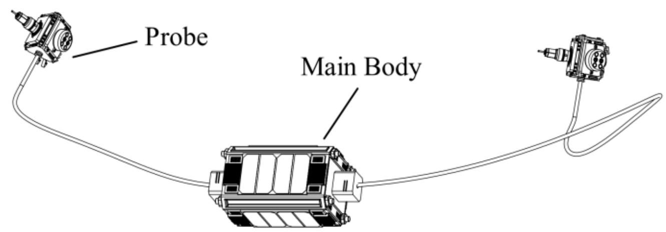

Figure 1. Structure of the CubeSat

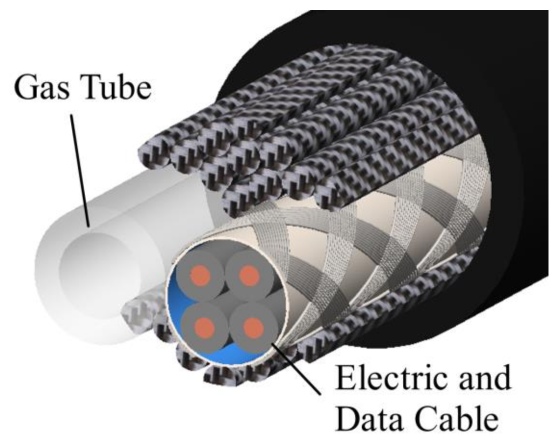

Figure 2. Structure of umbilical line

References

[1] Hruby V J, Deluccia C, Williams D. "Tethered Robot for Spacecraft Self Inspection and Servicing", 2018 AIAA SPACE and Astronautics Forum and Exposition, 2018, doi:10.2514/6.2018-5342.

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7th International Conference on Tethers in Space
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Learning-based Deployment and Retrieval Control of a Spinning Tethered Satellite Formation System

Caoqun Luo[1], Hao Wen[2], Dongping Jin[3]
1 City University of Hong Kong, Hong Kong, China, luo_caoqun@163.com
2 Nanjing University of Aeronautics and Astronautics, Nanjing, China, wenhao@nuaa.edu.cn
3 Nanjing University of Aeronautics and Astronautics, Nanjing, China, jindp@nuaa.edu.cn

Conference Topic: Fundamental Research on Space Tethers

Abstract: This paper investigates the deployment and retrieval problems of a spinning tethered satellite formation (TSF) system. A dynamic model of the spinning TSF system of concern is first developed to describe the attitude motions of the system, involving the relative rotations of the tethers to the central main satellite. Besides, tangling motions between the tethers and satellites may be generated and thereby destroy the system stability and safety in a short time during the tether deployment and retrieval process, especially for a spinning TSF system. How to control the attitude motions quickly and keep the formation stable is a challenging task. To this end, a learning-based control strategy with low time cost is proposed to achieve the stable deployment and retrieval of tethers. In the strategy, a nonlinear model predictive control (NMPC) law is developed for achieving stable deployment/retrieval of tethers, in which the control constraints and nonlinear dynamics are both accounted for. Based on a deep learning method, a dataset including control input and state output obtained offline using the NMPC law are trained to form a deep neural network. In this way, an online feedback control of the attitude motions of the system can be achieved by conducting real-time mapping from the system state to the control input using the neural network. Finally, numerical simulations of deployment and retrieval for the TSF system with symmetric and unsymmetric configurations are both presented to demonstrate the computational efficiency and to validate the effectiveness of the control strategy.

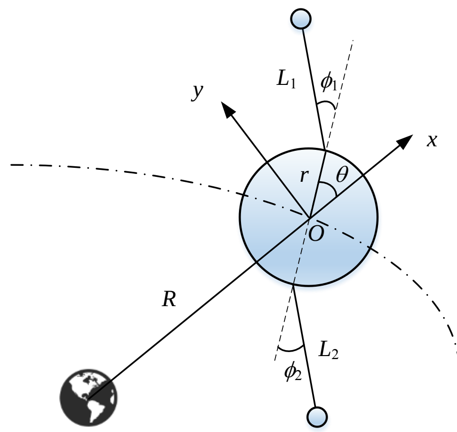

Figure 1. A spinning TSF system

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7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Tethered Artificial Gravity Assists for Capture about Binary Asteroids in the Circular Restricted Three-Body Problem

N. Pallotta[1], M.C.F. Bazzocchi[1,2,*]
[1] Astronautics and Robotics Laboratory (ASTRO Lab), Department of Mechanical & Aerospace Engineering, Clarkson University, Potsdam, USA
[2] Astronautics and Robotics Laboratory (ASTRO Lab), Department of Earth & Space Science & Engineering, York University, Toronto, Canada
* Corresponding Author: mbazz@yorku.ca, mbazzocc@clarkson.edu

Conference Topic: Tethered Spacecraft for Asteroid or Comet Exploration and Mining

The use of tethered artificial gravity assists in space travel to perform orbital maneuvers has the potential to significantly extend missions through the reduction of fuel consumption. As space exploration has become more accessible, interest in near-Earth asteroids (NEAs) has grown. Studying NEAs can yield new information about the early solar system and provide important insights into related fields, such as planetary defense. Further, it has been discovered that many NEAs are in binary systems, which presents a unique orbital environment for optimizing spacecraft maneuvers for future asteroid missions. This paper employs a genetic algorithm to determine optimal tethered maneuvers to periodic orbits in the vicinity of a binary asteroid using the circular restricted three-body problem (CR3BP). The optimization determines the maneuver that results in the greatest change in the Jacobi constant between the incoming orbit and final orbit in order to maximize the benefit of the tethered artificial gravity assist into a periodic orbit about the primary asteroid.

The utilization of tethers for artificial gravity assists has been studied as an alternative to traditional propulsion methods for over thirty years. Since then, the tethered gravity assist maneuvers have been investigated for use in many different missions and applications. For example, a tethered gravity assist about a moon to capture a spacecraft around a planet was explored to determine feasible tether detachment state vectors [1]. Similarly, tethered gravity assist maneuvers were proposed to hop between asteroids in the main belt for an extended mission that would use minimal fuel [2]. These studies found that in a mission that would travel to seven main belt asteroids, utilizing tethered maneuvers would reduce the necessary Δv generated via chemical propulsion from 235 m/s to 51 m/s [2]. This paper expands upon these previous investigations into the use of optimal tethered artificial gravity assists in fuel-saving maneuvers by applying the dynamics of the tethered maneuver in binary asteroid systems using the CR3BP.

The tethered gravity assists are examined within the context of the low-gravity environment of binary asteroid systems using CR3BP dynamics and the feasibility of maneuvers in binary systems of various mass ratios are explored. This investigation selected three observed binary asteroid systems with different mass ratios and orbital eccentricities that allowed for modelling using the CR3BP. Optimizations were performed and simulated to investigate and demonstrate the feasibility of tethered gravity assists in various binary asteroid environments.

In each analyzed system, the tethered artificial gravity assist was found to have the ability to significantly change the energy of the spacecraft and insert it into a desired planar, near-circular, periodic capture orbit about the primary. Figure 1 shows an example of an optimal tethered artificial gravity assist maneuver for a binary asteroid system. The developed approach aligned the detachment point with the desired final orbits about the primaries, with minimal error in the relative state vectors. Ultimately, the tethered artificial gravity assist maneuvers successfully redirected spacecraft from their initial trajectories into bound orbits within the binary systems, i.e., sufficiently changing the Jacobi constant of the spacecraft through the maneuvers.

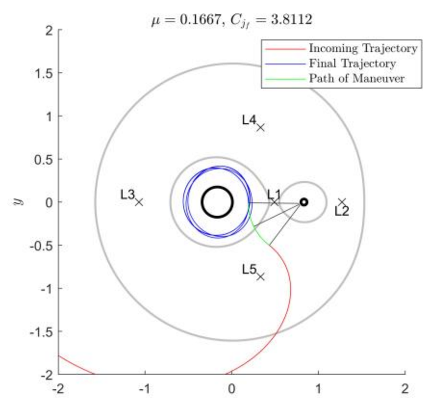

Figure 1. Example tethered artificial gravity assist maneuver with zero velocity curves corresponding to the final Jacobi constant

References

[1] A. F. Prado, "Using tethered gravity-assisted maneuvers for planetary capture," *Journal of Guidance, Control, and Dynamics*, vol. 38, no. 9, pp. 1852-1856, 2015.

[2] A. Wittig and D. Izzo, "Spiderman Spacecraft: Tethered asteroid hopping in the main belt," in *ESA*, 2016.

THE SEVENTH INTERNATIONAL CONFERENCE ON TETHERS IN SPACE

(June 5th, 2024)

ABSTRACT

Session 9 - Space Tether

Chair: Prof. George Zhu

- **Title:** Adaptive Fault-Tolerant Control and Its Experimental Verification of Spinning Tether System for Space Debris Removal (2024014)
- **Title:** The Three-Dimensional Maneuver Control of Spinning Tether System Under a New Lagrangian Model (2024012)
- **Title:** Detumbling Control of An Underactuated Tethered Satellite System (2024028)
- **Title:** Analysis of Fly-Around Mission with Spinning Tether System for Space Station Observation (2024010)
- **Title:** Data-Enable Control for Tethered Space Robot Deployment with External Disturbance (2024033)

Paper No: 2024014
7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Adaptive fault-tolerant control and its experimental verification of spinning tether system for space debris removal

P. Sun[1],C. Wang[1], Y. Zabolotnov[1,2], A. Li[1], H. Lu[1].
1 Northwestern Polytechnical University, Xi'an 710129, China, luhs@npwu.edu.cn
2. Samara National Research University, Moskovskoe sh. 34, Samara, 443086 Russia

Conference Topic: Tether-based Systems for Space Debris Remediation

As human space activities become more and more frequent, space environmental problems become increasingly severe. The main factor causing the deterioration of the space environment is the space debris generated by various space activities. Currently, there are a large number of malfunctioned satellites, rocket upper-stages and their debris in near-Earth space. In order to alleviate and change this situation, major space nations around the world are developing various effective space debris clearance mechanisms [1], an ideal platform of which is spinning tether systems [2]. The spinning tether system (STS) has advantages because of its non-contact and rapid de-orbit, spinning stability, and short preparation time for new tasks [3]. The spin-up process mainly relies on the main spacecraft and autonomous capture device thrusters, as well as the tether system tension control mechanism. Current research indicates that [1,2], during the ground development process, although modern technology and quality management methods can be used to eliminate various actuator faults as much as possible, the impact from debris capture is a great challenge to STS, and the system also needs to be accelerated to prepare for further tossing. At this stage, the system is prone to malfunctions, therefore, before executing actual space missions, it is necessary to design fault-tolerant control strategies and conduct a series of verification experiments on the ground.

In this paper, we consider the above problems and study the design of fault-tolerant control strategies for the post-capture spin-up process and ground verification. First, the Lagrangian equation is used to establish a dynamic model and analyze the failure mode of the thrust force of the actuator; then, the impact of the failure mode on the spin motion is analyzed, and an adaptive fault-tolerant controller is designed under fault conditions. Finally, in order to simulate actuator failure and verify the effectiveness of the control strategy, a ground experimental platform simulating three-dimensional tether spin was built as shown in Figure 1. Based on this test bed, the STS motion under uncontrolled conditions and when the system fails was studied, and the effectiveness of the proposed adaptive control strategy was further verified. Both numerical simulation and ground simulation results show that the designed controller can achieve stable spinning motion of the system after capture, and the controller is implementable for the actual hardware.

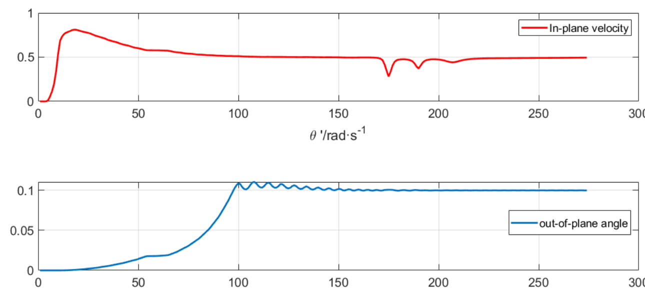

Figure 1. Curve of state variable change during STS spin-up process

(a) Physical picture (b) 3d model assembly picture

Figure 2. Rotary Test Bench

References

[1] Aslanov V S, Ledkov A S. "Survey of Tether System Technology for Space Debris Removal Missions",Journal of Spacecraft and Rockets, 2023: 1-81.
[2] Trushlyakov V, Yudintsev V. "Dynamics of rotating tethered system for active debris removal",Acta Astronautica, 2022, 195: 405-415.
[3] Lu H, Li A, Wang C, et al. "Tether Deformation of Spinning Electrodynamic Tether System and Its Suppression with Optimal Controller", Journal of Aerospace Engineering, 2021, 34(2):04021003

Paper No: 2024012
7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

The three-dimensional maneuver control of spinning tether system under the description of spinning vector

C. Sun[1], C. Wang[1], H. Lu[1], A. Li[1]
1 School of Automation, Northwestern Polytechnical University, Xi'an 710129, China, luhs@nwpu.edu.cn

Conference Topic: Mathematical Modeling of Space Tethers, Dynamics, Controls

With good centrifugal stability and significant tossing ability, spinning tether systems (STSs) are considered good solutions to the construction of artificial gravity, satellite formations, in-orbit transportation systems, etc. Due to the following reasons, the current research on STS is mostly focused on in-planar spinning motion [1]: The conventional Lagrangian models have singularities in the case of large out-of-plane angles, while the commonly used Newtonian models described in the inertial coordinate system suffer from the coupling problem when calculating in-plane and out-of-plane angles from Cartesian coordinate. Such problems put challenges to the further application of STS in missions like artificial gravity and satellite formations as they require spatial and maneuverable spins.

Based on the above problems, this paper investigates the three-dimensional maneuvering of tether spinning motion. First, in order to solve the aforementioned modeling problems, as shown in Fig. 1, this paper proposed a new spinning coordinate system $CX_rY_rZ_r$ by defining the spinning vector $\mathbf{n}_r$ denoting tether spinning motion, where λ is the angle between the projection of the spinning vector(CX_r) and the CX_c of the orbital moving coordinate system, η is the angle between the spinning vector and the orbital plane, and ψ is the spinning angle. Accordingly, a modified Newtonian-Eulerian model was established, and the calculation of spinning motion from the Cartesian inertial coordinate system was derived under the description of the spinning vector $\mathbf{n}_r$.

Second, this paper studied the maneuvering strategy between typical spinning planes, and reference trajectories for spinning plane maneuvering were given in the new spinning coordinate system $CX_rY_rZ_r$. In the end, a saturated closed-loop control law was designed to track the reference maneuvering trajectories, as small-thrust electrical engines are chosen as the active maneuvering and holding force. Fig. 2 shows STS motions during a maneuver process under the action of the open-loop reference output and the closed-loop controller. Simulation results show that by using the description of spinning vector, coupling problems of conventional STS models are avoided, and the proposed strategy can ensure three-dimensional maneuvering of STS spinning motion. During the maneuvering process, the errors of angles λ.η are 0.007 rad (relative error 0.45%), and the error of spinning velocity $\dot{\psi}$ is 0.00002rad/s (0.30%).

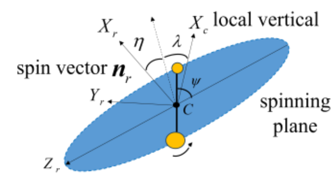

Figure 1. The spinning plane coordinate system

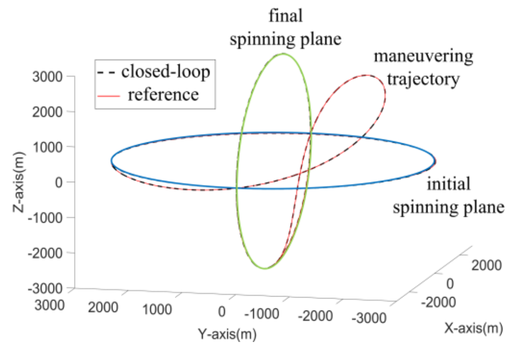

Figure 2 (a) Trajectory of sub-satellite during maneuvering

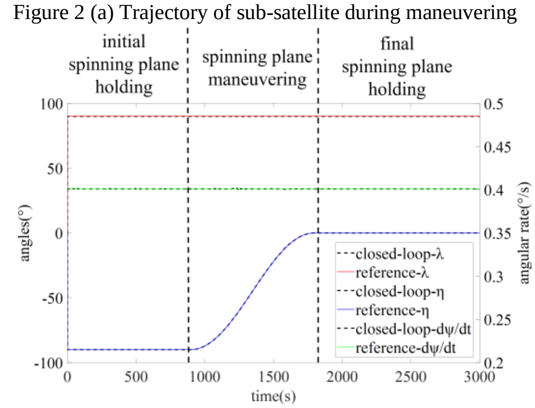

Figure 2 (b) λ , η and $\dot{\psi}$ of STS during maneuvering

References

[1] Lu, H., Li, A., Wang, C., and Zabolotnov, Yu. M. "Stability analysis and motion control of spinning electrodynamic tether system during transition into spin", Acta Astronautica, Vol. 177, pp. 871–881, 2020, doi: 10.1016/j.actaastro.2019.11.032.

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7th International Conference on Tethers in Space
June 2-5, 2024, Toronto, ON, Canada

Detumbling control of an underactuated tethered satellite system

Yajie Cheng[1], Lingling Shi[1], Minghe Shan[2*]
1 School of Mechanical Engineering, Beijing Institute of Technology, Beijing, China
2 School of Aerospace Engineering, Beijing Institute of Technology, Beijing, China, shanminghe@gmail.com

Conference Topic: Space Tether Technology Development and Experimental Studies (Subsystem Technologies to Enable Space Tether Missions)

Net capturing is a promising method to remove space debris objects due to its multiple advantages. We focus on the system stabilization during the post-capture phase where faces two mainly problems, underactuated control and uncertainty interference. Referring to the previous studies, propulsion adjustment [1-2] and attitude control [3] are the common methods to stabilize the combined tethered system. The aim of our research is to enhance the robustness of the system without adding additional equipment. As shown in Fig.1, we have implemented hierarchical sliding mode control (HSMC) method to stabilize the combined tether system solely by controlling the chaser satellite [4]. Numerical simulations have demonstrated its efficiency and robustness for the post-capture stabilization of the combined tethered system.

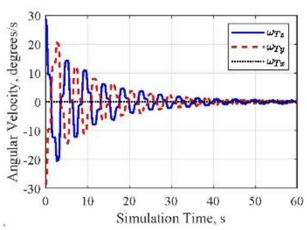

Figure 1 Angular velocity of the target under HSMC control[4]

However, there are still some open problems. One is the vibration between two end bodies due to the flexible tether, which will produce the unstable tether tension. The other problem is the decline in platform maneuverability. We add a commonly used reel in/out mechanism to control the uncooperative target. Unlike previous constant tension control methods [5], we utilize a closed loop tether tension control with respect to the target status. The basic principle of the control method can be described as that tether tension will increase as the target deviates from the equilibrium position. In the terms of specific implementation, the corresponding propulsion force adjustment and tether length control are the keys to achieving stable variable tension. As shown in Fig.2 and Fig.3, numerical simulations for double axes rotation target demonstrate that the proposed method is able to achieve stable tether tension and high detumbling efficiency. Furthermore, we will carry out ground experiments to validate the feasibility of the tether tension control based on our newly designed free-flying robots.

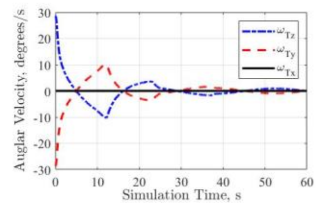

Figure 2 Angular velocity of the target under tether tension control

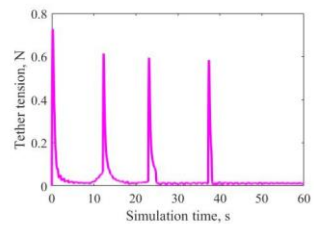

Figure 3 Tether tension in main tether

References

[1] Shan M, Shi L. Post-capture control of a tumbling space debris via tether tension[J]. Acta Astronautica, 2021, 180: 317-327.
[2] Shan M, Shi L. Velocity-based detumbling strategy for a post-capture tethered net system[J]. Advances in Space Research, 2022, 70(5): 1336-1350.
[3] Kang J, Zhu Z H, Santaguida L F. Analytical and experimental investigation of stabilizing rotating uncooperative target by tethered space tug[J]. IEEE Transactions on Aerospace and Electronic Systems, 2021, 57(4): 2426-2437.
[4] Shi L, Cheng Y, Shan M. Detumbling of Underactuated Tethered Satellite System Based on Hierarchical Sliding Mode Control[J]. Journal of Guidance, Control, and Dynamics, 2023: 1-15.
[5] Meng Z, Wang B, Huang P. GEO debris towing removal using reel control of tethered space robots[C]//2017 IEEE International Conference on Robotics and Biomimetics (ROBIO). IEEE, 2017: 2231-2236.

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June 2-5, 2024, Toronto, ON, Canada

Mission analysis of tethered fly-around satellite formation for space station observation

H. Yang[1], C. Wang[1], H. Lu[1], A. Li[1], Y. Zabolotnov[2]

[1] School of Automation, Northwestern Polytechnical University, China, luhs@nwpu.edu.cn

[2] Samara National Research University, Russia

Conference Topic: Other Advanced Tether Concepts

Fly-around satellite formation observation plays a crucial role in monitoring the space station's status, providing early warning and active defense against unknown threats[1]. However, traditional satellite fly-around methods have certain limitations: 1) Fast-controlled fly-around relies on impulsive thrust, which consumes a significant amount of fuel and cannot sustain long-term monitoring effects. 2) natural fly-around, involving multiple orbit changes and gradual approach control, demands extremely high measurement and control accuracy. Moreover, due to the extended fly-around period, it fails to achieve comprehensive and real-time monitoring effects[2]. In both cases, the frequent fly-around observation of space station for a long and sustainable time is barely feasible using conventional techniques.

To address the aforementioned issues, as shown in Fig.1, this study proposed a novel tethered fly-around satellite scheme. The scheme involves deploying two tethered satellites to designated positions around the space station, and forming a three-body linear tethered satellite formation system. These satellites then spin up to the desired spinning state, enabling periodical observation of the space station. Considering the various requirements of fly-around missions, we defined three different spin planes under the orbital coordinate system $o-xyz$: the planar plane (xoy), the vertical plane (xoz), and the horizontal plane (yoz). The satellite can be deployed to three distinct positions in these planes. Subsequently, spin strategies are proposed for three typical observation trajectories (scheme I, scheme II, scheme III).

To analyze the mission feasibility of the proposed schemes, we conducted a comparison of fuel consumption between the three tethered spinning fly-around schemes and the corresponding untethered fly-around scheme within one orbital period. The satellites used in the simulation are 20kg, and the deployed tether lengths are 2km. As shown in Table 1, the results indicate that tethered satellites consume significantly less fuel than untethered satellites. Consumption analysis indicates that, during Planar spin, a 97.5% saving of impulse can be achieved compared to the conventional untethered fly-around. On the other hand, the tethered fly-around scheme achieves a 75% reduction in the vertical plane, and a 86% reduction in the horizontal plane. Based on this analysis, we can conclude that tether connection allows for frequent circumferential and omnidirectional observations with minimal fuel consumption, as the tethered fly-around process does not involve complex orbit maneuvers. It is noteworthy that the planar spin can be sustained with little consumption after spin-up, while the horizontal and vertical spins require more fuel for maintenance. The aforementioned analysis demonstrates the significant potential of tethered fly-around techniques for future space technology applications.

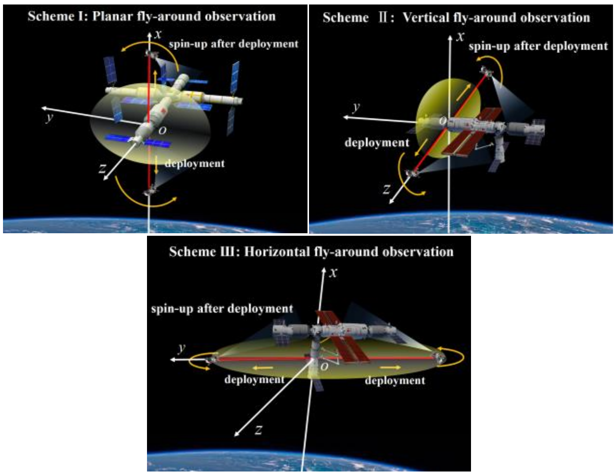

Figure 1. Schematic diagram of tethered fly-around satellite formation

Table 1. Comparison of impulse with/without tether within 1 orbital period

Traditional fly-around	Tethered fly-around
Scheme I (Planar) Impulse consumption (29720 N.s)	Scheme I (Planar) Impulse consumption (720 N.s)
Scheme II (Vertical) Impulse consumption (21800N.s)	Scheme II (Vertical) Impulse consumption (5390N.s)
Scheme III (Horizontal) Impulse consumption (25000 N.s)	Scheme III (Horizontal) Impulse consumption (3410 N.s)

References

[1] Sun, C., Sun, Y., and Yu, X., et al. "Rapid detection and orbital parameters' determination for fast-approaching non-cooperative target to the space station based on fly-around nano-satellite", Remote Sensing, Vol. 15, pp. 1213, 2023.

[2] Guo, J., Ma, K., and Yao, Y. "Orbit and control design for forming and keeping fly-around", 2009 Chinese Control and Decision Conference. IEEE, pp. 729-734, 2009.

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Data-Enable Control for Tethered Space Robot Deployment with External Disturbance

Ao. Jin[2], Fan. Zhang[1], Panfeng. Huang[1]
1 Research Center of Intelligent Robotics, School of Astronautics, Northwestern Polytechnical University, Xi'an, China, fzhang@nwpu.edu.cn
1 Research Center of Intelligent Robotics, School of Astronautics, Northwestern Polytechnical University, Xi'an, China, pfhuang@nwpu.edu.cn
2 Research Center of Intelligent Robotics, School of Automation, Northwestern Polytechnical University, Xi'an, China, jinao@mail.nwpu.edu.cn

Conference Topic: Mathematical Modelling of Space Tethers, Dynamics, Controls

The space debris removal is extremely urgent for the space safety. Owing to the advantages in terms of flexibility, transportability and safe manipulation [1], tethered space robot (TSR) has good foreground for space debris removal missions. But the main challenge of tethered space robot for now is how to deploy it safely with external disturbance in the space. And disturbance existed in the deployment missions is complicated and multi-source, which is a great deal of difficulty for the deployment. While there is not an effective way to capture external disturbance entirely during the deployment for now. Recently, machine learning based methods have been successful in estimating external disturbance and designing stable controller of complex control problems [2], [3]. One of benefits of these machine learning based methods is that they do not need any prior knowledge of the disturbance and the plant but only the input and output data of plant. This provides more possible options of designing disturbance observer and stable controller for complicated task. Therefore, a learning-based framework is proposed to estimate external disturbance and design stable controller for tethered space robot deployment mission in this work.

The proposed framework contains two parts: offline training and online control with trained disturbance model. For the offline training, a disturbance model and stable controller is trained for online control. The learning scheme of predicting disturbance utilized in the proposed framework is meta-learning [4], which could learn disturbance model from input and output data of tethered space robot across different conditions. And spectral normalization [5] is employed to bound the Lipschitz constant of deep neural network of meta-learning, which aims to constraint the output of neural network and improve generalization. A stable tracking controller for deploying tethered space robot is using control contraction metric (CCM) to guarantee the convergence. And the controller and metric are also parameterized by neural networks. Then some of essential loss functions are developed for training disturbance model and controller. For the online control, the learned disturbance model and tracking controller obtained from offline training is used to estimate the external disturbance and generate control signals respectively. When there are new measurements of tethered space robot coming, the learned disturbance model outputs the estimated disturbance and the learned controller generates control signals to the actuators of deployment unit with the estimated disturbance. And with the convergence guarantee, the tethered space robot will be deployed to the destination safely.

The proposed framework of this work is expected to estimate multi-source and complicated disturbance existed in the space effectively across various conditions and have better control performance than other methods with convergence guarantee.

The anticipant contributions of this work contain the following: 1) A learning-based method is proposed to estimate the external disturbance during the tethered space robot deployment using meta-learning without any prior knowledge of disturbance. 2) The proposed framework has better control performance with learned tracking controller using control contraction metric and the trained disturbance model, which is expected to deploy the tethered space robot more quickly.

References

[1] P. Huang *et al.*, “A review of space tether in new applications,” *Nonlinear Dyn.*, vol. 94, no. 1, pp. 1–19, Oct. 2018, doi: 10.1007/s11071-018-4389-5.
[2] M. O'Connell *et al.*, “Neural-Fly enables rapid learning for agile flight in strong winds,” *Sci. Robot.*, vol. 7, no. 66, p. eabm6597, May 2022, doi: 10.1126/scirobotics.abm6597.
[3] G. Shi *et al.*, “Neural Lander: Stable Drone Landing Control using Learned Dynamics,” in *2019 International Conference on Robotics and Automation (ICRA)*, May 2019, pp. 9784–9790. doi: 10.1109/ICRA.2019.8794351.
[4] T. M. Hospedales, A. Antoniou, P. Micaelli, and A. J. Storkey, “Meta-Learning in Neural Networks: A Survey,” *IEEE Trans. Pattern Anal. Mach. Intell.*, pp. 1–1, 2021, doi: 10.1109/TPAMI.2021.3079209.
[5] P. Bartlett, D. J. Foster, and M. Telgarsky, “Spectrally-normalized margin bounds for neural networks.” arXiv, Dec. 05, 2017. doi: 10.48550/arXiv.1706.08498.