


The Sixth
INTERNATIONAL CONFERENCE ON
TETHERS *in* SPACE

Book of Abstracts

Hosted by Universidad Carlos III de Madrid, June, 12-14, 2019

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INTERNATIONAL CONFERENCE ON

TETHERS in SPACE

Hosted by Universidad Carlos III de Madrid, Spain

June 12-14, 2019

BOOK OF ABSTRACTS

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TiS 2019 Key Information

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Conference Website: http://eventos.uc3m.es/go/TiS2019

University Website: https://www.uc3m.es

Internet Wifi Network: UC3M-Events

Social Event: Thursday (May 13th)

- 19:00, Visit to Reina Sofia Museum. Sabatini Building, c\ Santa Isabel, 52, Madrid.
- 20:15, Conference dinner at Arzábal Restaurant. Sabatini Building, c\ Santa Isabel, 52, Madrid.

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UC3M Organizing Committee

The Sixth International Conference on Tethers in Space 12-14th June 2019, Madrid

TiS 2019 Organizing Committee

Universidad Carlos III de Madrid

Dear TiS2019 participants,

Welcome to the Sixth International Conference on Tethers in Space. After the successful TiS 2016 in Michigan, tether community meets again for sharing the last advances in tether technology. We hope that this event will be a unique platform for boosting tethers and will reinforce the cooperation among research groups, industry, and space agencies.

TiS 2019 Technical Committee, listed in page 11, has prepared a scientific programme that includes:

- Three invited talks by
    - Franco Malerba, first Italian Astronaut who flew in 1992 for an eight-day mission that tested the Tethered Satellite System
    - Ivan Bekey, president of Bekey Designs, Inc, and former NASA Director of Advanced Programs.
    - Jose González del Amo, Head of the Electric Propulsion Section at ESA and the ESA Propulsion Laboratory Manager.
- Oral talks (one session on Wednesday and Friday and two parallel sessions on Thursday).
- A poster session on Thursday.
- An open discussion on overcoming impediments for space tether flight demonstrations (Friday).

TiS 2019 will also bestow the Mario Grossi Award to the best work by a young scientist (PhD students or postdocs).

We thank to the anonymous reviewers that revised all the abstracts submitted to TiS 2019 and to the authors that made possible a unique and high-quality conference on tether technology. As highlighted by this Book of Abstracts, space tethers constitute an active field of research with programmed missions in the following years. There are excellent perspectives in terms of academia-industry collaboration and applications.

We would like to thank to our sponsors for their support to this conference, to our colleagues, and also to UC3M administrative staff, which helped us with the organization of this event. We are very grateful to S. G. Bilén,,B. E. Gilchrist, and L. Johnson for their advices and providing a smooth an effective transition from TiS 2016 to TiS 2019. The Organizing Committee wishes all the participants a pleasant stay in Madrid, a gorgeous city with an amazing variety of cultural activities. We really look forward meeting you in a new and exciting edition of TiS Conference.

Sincerely,

TiS 2019 Organizing Committee

Tethers in Space, a fascinating technology of the first Italian manned mission…the best has yet to come

F. Malerba

Académie de l'Air et de l'Espace

Franco Malerba
First Italian Astronaut
Academie de l'Air et de l'Espace

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Keynote Speaker

The STS-46 mission of the Space Shuttle Atlantis in 1992 tested in orbit a novel technology: « tethers in space ». The Italian Science Community was particularly engaged and proud of this mission because two Italians - Bepi Colombo and Mario Grossi – were considered as fathers of the Tethered Satellite concept, the Investigators' team included distinguished members of the US Science Community and the Italian Industry Alenia Spazio was responsible of the design and manufacture of the Tethered Satellite itself, under the management of the newly born Italian Space Agency. An additional element of Italian pride and people's curiosity was the participation of an Italian Scientist as Payload Specialist, a member of the astronauts' team.

The TSS1 mission scientific program was very ambitious. First overarching operational goal was to test and demonstrate the feasibility of the deployment and retrieval of a tethered satellite. The scientific goals aimed at investigating the interaction of a highly charged conductive body in the ionospheric plasma, at demonstrating the electric power generation capability of the tethered system interacting with the Earth Magnetic field, and at testing the generation of ELF waves.

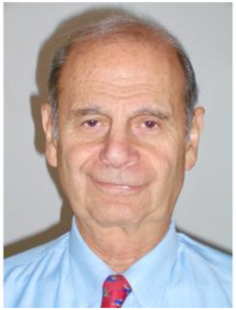
The mission was curtailed by a mechanical blockage caused by a load-bearing bolt improperly screwed on in the final installation of the deployer system in the Shuttle cargo bay, which limited severely the length of the cable deployed. In spite of the relatively short length of the deployed cable, scientists gathered encouraging scientific results, the satellite was successfully retrieved and the two agencies - NASA and ASI - decided to carry out a reflight of the Tethered Satellite System in 1996. During the second mission, the cable was indeed fully deployed up to its 20 kilometers length but an electric arc suddenly severed the cable and the satellite was lost. The technology of Tethers in Space suffered inevitably a setback.

Tethers in Space, in spite of their difficult operations, have great potential both in science and in engineering. I will suggest a few examples: (1) providing astronauts' spacecraft with artificial gravity (2) exploiting momentum transfer during in-orbit servicing of satellites or space platforms (3) deorbiting "space debris" either by electrodynamic tethers or by flexible systems (nets), (4) exploring upper layers of the stratosphere with tethered sensors (5) developing fantastic "space elevators".

A historical perspective on how the space tethers field of endeavor started, difficulties faced, and lessons learned

Ivan Bekey

The Aerospace Corporation.



Ivan Bekey
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Keynote Speaker

My talk will begin with the principal events that led to trying to understand the physics of space tethers and then to identify their principal potential application areas; and the key roles played by the pioneers in this field. The talk will discuss some of the main difficulties that presented themselves and that we had to face when advocating the use of space tethers in the early days, including obtaining financial and organizational support for their development and test; and the attitudes of the technical community and of the space agencies in this time frame. The talk will then address how I believe that space tethers are viewed these days as seen through the different eyes of governments, academia, and private industry.

The talk will conclude with a view of the future for space tethers and their potential applications which hopefully will help mission designers to implement the lessons learnt to the development of these new space systems

José González del Amo
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Space Electric Propulsion Missions in Europe, a lesson learned for the Tether Technology

José González del Amo
European Space Agency

Keynote Speaker

In the commercial arena (telecommunication and constellations space missions), the strong competition among satellite manufacturers is a major driver for advancements in the area of electric propulsion, where increasing better performance together with low prices are required. Furthermore, new scientific and Earth observation missions dictate new challenging requirements for propulsion systems and components based on advanced technologies such as microNewton thrusters. Moreover, new interplanetary missions in the frame of exploration will require sophisticated propulsion systems to reach planets such as Mercury or Mars and in some cases bring back to Earth samples from these planets. Finally, Electric Propulsion systems will be used by the future EVO Galileo programme to perform orbit raising manoeuvres to allow a great reduction of the launcher price.

ESA is currently involved in activities related to spacecraft electric propulsion, from the basic research and development of conventional and new concepts to the manufacturing, Testing and flight control of the propulsion subsystems of several European satellites. The exploitation of the flight experience is also an important activity at ESA which will help mission designers to implement the lessons learnt to the development of these new propulsion systems. ESA missions such as Artemis, Smart-1, GOCE, Alphabus and Small-GEO have paved the way for the use of electric propulsion in future ESA missions: Bepi Colombo, Neosat, Electra, LISA etc.

The experience of electric propulsion in space missions, the way the electric propulsion technology was adopted by space mission designers could help the tether community to foster the use of this technology in space.

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Stability Analysis and motion control of electrodynamic spinning tether system during transition into spin

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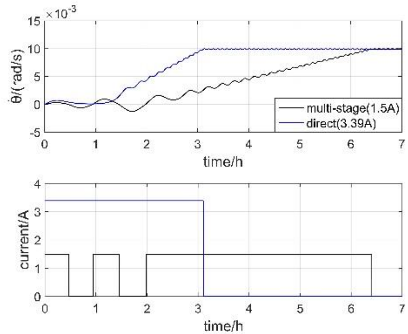
Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

Electrodynamic spinning tether system is considered as one of the promising applications of tethered satellite systems, which requires little fuel and surpasses the equilibrium limit of conventional electrodynamic tether systems. It has good prospects in debris removal, orbit reboost, payload transportation and so on. It has been found in this paper that, the most vulnerable stage is the transition from the equilibrium state into spinning state. If not carefully controlled, tether is easy to become slack during such process.

In this regard, by considering aforementioned problems, this paper mainly focuses on the transition of tether system from the initial equilibrium state into the final expected spinning state. Motion of electrodynamic spinning tether system is described by Langrangian model. Conditions of dynamic equilibrium and minimum critical currents for acceleration are derived in this paper. Such conditions provide empirical references for future space tether experiments. Two control methods are proposed for transition manoeuvres in different mission backgrounds. The first method (so-called direct transition) provides a near time-minimum solution. Second method is the so-called multi-stage swing transition, which provides a minimum current-energy solution for acceleration into spin. Considering inhomogeneous distribution of magnetic induction, an adaptive sliding mode controller is proposed to track nominal trajectory of acceleration. Effectiveness of the proposed control methods are validated by numerical results.



System behaviour under two proposed control methods

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Command filter based on back-stepping control for deployment of an electro-dynamic tether system

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Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

This paper studies adaptive back-stepping control for deployment of an electro-dynamic tether system with the consideration of uncertainty of external disturbances and unmodeled system dynamics. Command filter design is developed to achieve the controller, which can remove the inherent problem of “explosion of complexity” in back-stepping. Furthermore, introducing the auxiliary system can eliminate the effect of the error caused by the command filter. Under the proposed control law, the stabilization of the system states is proved via the Lyapunov theory. Finally, simulation results show the deployment of electro-dynamic tether system based on the presented control strategies.

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Adaptive sliding mode control for deployment of electrodynamic tether via limited tension and current

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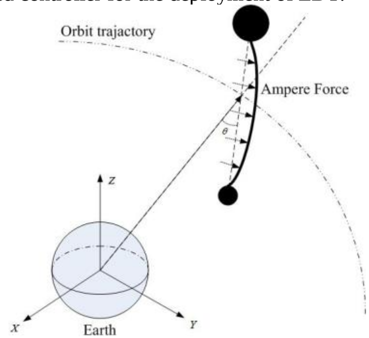
Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

Electrodynamic Tether (EDT) system has shown its broad application prospects in space technology. Deployment process of electrodynamic tether is the pre-condition for space tether missions. A common operation mode of EDT is to keep the tether non-current carrying in deployment process and energize the fully deployed conductive tether in deorbit. It is worth noting that the tether attitude motion will be influenced by excitation of electrodynamic force [1], which also provides the possibility to be used as a kind of control force. This paper studies the deployment control problem of EDT via a hybrid tether tension and current regulation without chemical propulsion.

The dynamic model of EDT is derived considering the tether bend characteristics. From the point of EDT performance efficiency, the approximative equilibrium position near local vertical is the most concerned. For this reason, the approximative equilibrium conditions which are regarded as the deployment control goals are analyzed. After that, current auxiliary deployment strategy is proposed to deploy EDT to the approximative equilibrium position with desired tether length and in-plane angle, and synchronously guarantee stabilization of the in-plane motion. In order to augment resist disturbance capacity of control system, a deployment controller based on Adaptive Sliding Mode Control (ASMC) is proposed with inputs limitation which are introduced by using a pair of saturation functions to ensure that tether tension is always non-negative and current is within limits. Finally, the stability characteristics of system under the presented hybrid controller are studied based on Lyapunov theory. Numerical simulation results validate effectiveness of the proposed controller for the deployment of EDT.



The diagram of EDT system

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Launching a Spacecraft Using an Electrodynamic Tether with an Inflatable Balloon

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SAMARA UNIVERSITY

Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

The stage of putting a spacecraft into orbit is an integral part of any space program. At present, multistage rockets are used to solve this problem. The application of an auxiliary reusable space tether system can reduce the cost of the launching operation due to avoiding the use of carrier rockets upper stages. Within the framework of the considered transport operation it is assumed that the space tether system is in a low circular Earth orbit in a steady state close to the local vertical. The spacecraft is put into low orbit by a light rocket, and it docks to the lower end of the tether. Then the space tether system is transferred into rotation. The spacecraft is separated from the tether when the system makes a half turn around its center of mass. After separation, the space tether system is transferred to its initial steady state. Thus, the height of the spacecraft's orbit is increased without the cost of fuel.

The feature of this study is the use of an inflatable balloon built into the lower tethered module for the tether twisting. The balloon inflation leads to a significant increase in the aerodynamic drag force acting on the lower end of the tether system. This will cause the tether system to start turning. If the balloon area is large enough, the initial position of the system will cease to be a position of stable equilibrium, and the system will go into rotation. Previous study has shown that the space tether system altitude quickly degrades as a result of the drag force impact [1]. To solve this problem, it is proposed to use an electrodynamic tether. The aim of the work is to study the dynamics of the space tether and the development of the control laws for electrodynamic tether to prevent the negative effects of the atmosphere and to return the tether system to its initial state after the manoeuvre.

The mathematical model of the space tether system was developed using Lagrange formalism. The plane motion of the system was considered. The influence of the atmosphere on the tethered bodies was taken into account. The analysis of the influence of the mass-geometric parameters of the system on the form of phase portraits was carried out. The control laws of the electrodynamic tether current were proposed to prevent a drop in the height of the tether system orbit at the stage of waiting for the docking and to transfer the system into its initial state after the spacecraft separation. The effectiveness of the laws was confirmed by the results of numerical simulations.

This study was supported by the Russian Foundation for Basic Research (Project No. 18-31-20058 mol_a_ved).

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Review of KITE – Electrodynamic Tether Experiment on HTV-6 –

Y. Ohkawa[1], S. Kawamoto[1], T. Okumura[1], K. Iki[1], H. Okamoto[1], K. Inoue[1], T.Uchiyama[1], D. Tsujita[2], and KITE team[1]

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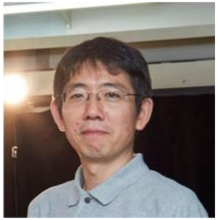

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Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

An on-orbit experiment of an electrodynamic tether (EDT) was conducted on the H-II transfer vehicle 6 (HTV-6). Primary objective of this experiment was to demonstrate essential technologies of the EDT aiming at the application to future active debris removal. The mission is called KITE, Kounotori Integrated Tether Experiment.In the KITE mission, deployment of a 700-m-length bare tether and driving of 10-mA-level tether current were planned. The major components for KITE are the bare tether, reels for tether housing and braking, end-mass, releasing mechanism of the end-mass, camera for tether dynamics observation, field emission cathode (FEC), multi-functioned plasma potential monitor (LP-POM), magnetic sensor, and data handling / power control unit.

The HTV-6 was launched on December 9, 2016 and the KITE mission was conducted from January 28 to February 5, 2017, following the unberthing of the HTV from the International Space Station (ISS). Figure 1 shows the photo of the HTV taken from the ISS just after the release.

Following the initial checkout of the KITE components, the end-mass ejection process for tether deployment was pursued, however, the end mass could not be released due to the malfunction of the releasing mechanism.

Although the tether deployment was unsuccessful, other KITE components operated well without critical trouble. On the FEC operation, the electron emission characteristics depending on ionospheric plasma conditions and endurance characteristics in the low Earth orbit (LEO) were obtained. The maximum electron emission current reached over 5 mA. The LP-POM measured electrical charging behaviour of the HTV and ionospheric plasma current throughout the HTV orbiting in LEO. These results are beneficial to future development of EDT and other space applications.

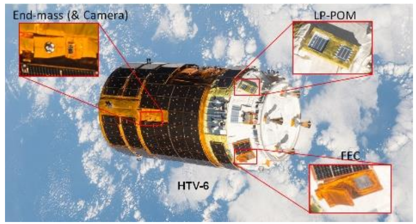
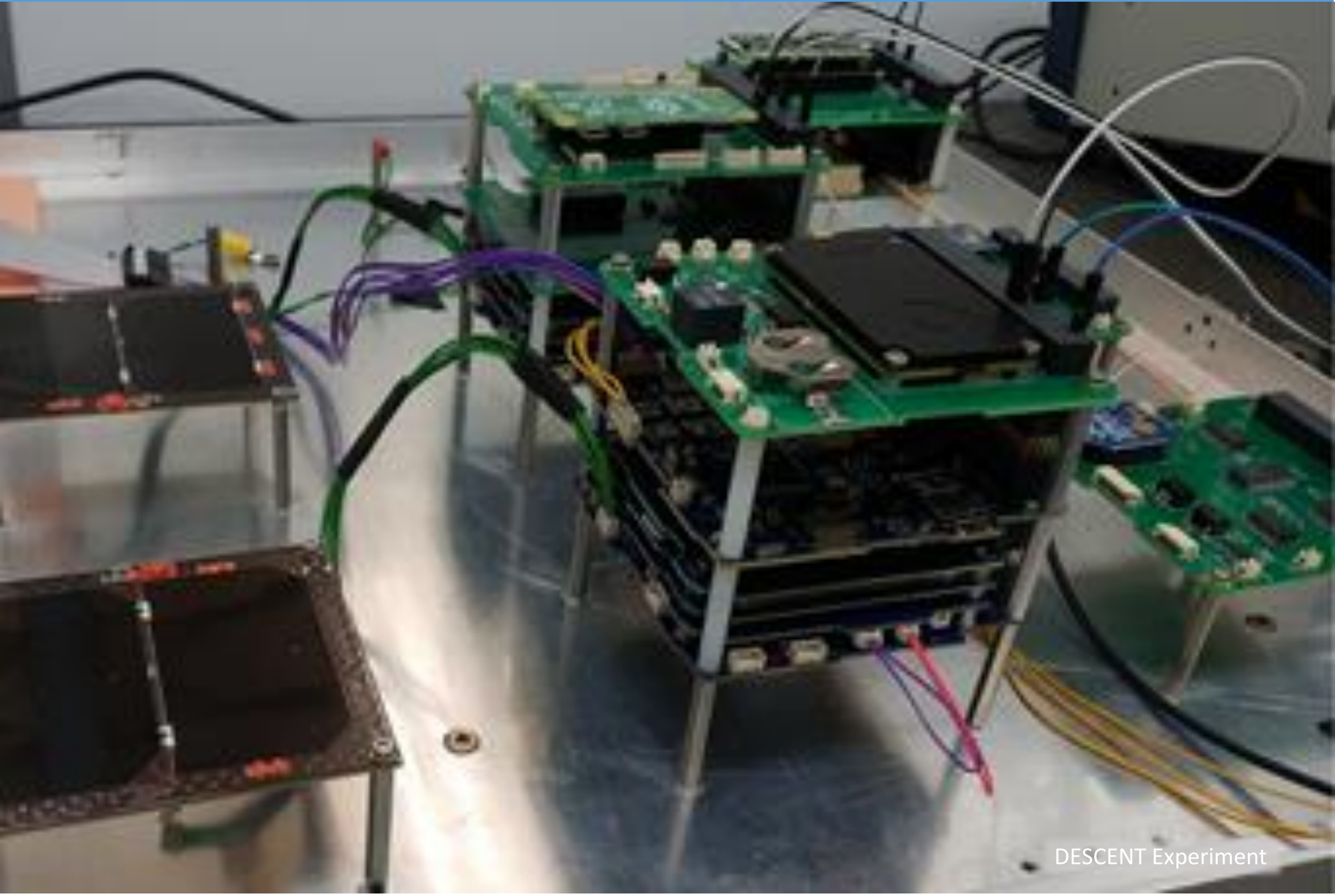


Fig. 1 KITE components on HTV-6.



DESCENT Experiment

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Electrodynamic Tether Mission - DESCENT

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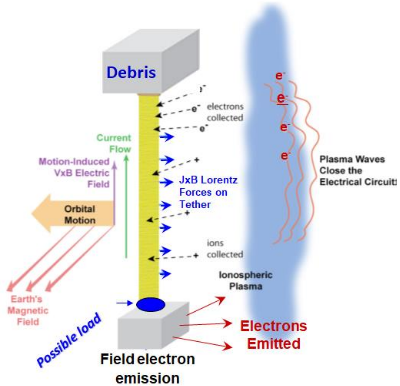
Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

Electrodynamic Tether (EDT) is a new type of propulsion for spacecraft that does not consume propellent. It is formed by a conductive tether connecting two end bodies. EDT possesses a unique capability to lower or boost spacecraft orbits, power generation, and deorbit space debris, without consuming propellant. The EDT propulsion builds on two fundamental principles of electromagnetism: electromotive force is produced when a conductive wire moves through a magnetic field, and the field exerts a force on the current carrying wire. This type of space propulsion has advantages of propellentless, low mass, compact size, ease of use and low cost, compared with its counterpart of rocket propulsion. It is very appealing for the application of space debris removal. This paper introduces a new EDT mission - DESCENT from mission concept study, to mission objectives, nanosatellite design, hardware selection, AIT, and operation. The mission involves two 1U-CubeSats connected by a 100m long conductive EDT. Two CubeSats will be launched as one unit into orbit from the International Space Station and subsequently separated to deploy the EDT with gravity gradient. The mission is to demonstrate the deployment and stabilization of an EDT system, electrical current generation and satellite deorbit in space. In addition, the mission will provide an innovative approach to improve the interpretation of convective motion in the F-region ionosphere at high latitudes. The latter will provide unique information for radio scientists, which is inaccessible on Earth, to characterize radio frequency plasma wave emissions or calibrate HF radar equations. It should also note that the EDT technology can be further used in the future as propellantless space elevator to transport the space assets from one or-bit to another.



Electrodynamic Tether Mission Concept.

The Electric Model of Experimental Electrodynamic Space Tether System.

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Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

The report considers the electric model of passive electrodynamic space tether system (EDTs), i.e. such EDTs, in which additional contactors with plasma are not provided. This model was developed in the framework of the project of a small experimental EDTs [1]. The model is based on the probe theory and the equality of the electron and ion currents collected by the system in the ionospheric plasma. The model makes possible to calculate the experimental EDTs parameters ensuring the existence of the anodic and cathodic parts of the system for the selected orbit, as well as predicting the voltages and currents in the parts of the system. In contrast to the previously known model, the proposed model makes it possible to more simply carry out calculations and assess the effects of the interaction of a system with plasma, and also to take into account a number of additional factors that can make significant corrections to the operation of the system. In particular, it is shown that the current collected by the end bodies of the system may have a significant impact on the total current in the system.

One of the most difficult and interesting tasks is to collect the ion current by a negatively charged body. The application of the Alpert-Lem model [2] for a current bounded by a layer shows interesting possibilities for significantly increasing the current in the system by increasing the surface area of a negatively charged body. However, the coefficients of the Alpert-Lem model were empirically determined from the results of the TSS-1R experiment for the electron current to a positively charged body. The creation of mathematical models of the ion current collecting by a negatively charged body with high potential needs experimental research.

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Orbital experiments with electrodynamics tether systems

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Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

The further development of electrodynamic tether systems (EDTs) at the present stage of their creation is connected with obtaining experimental data on the interaction of EDTs with the external environment and the system dynamics in Low Eearth Orbits. Large-scale and expensive experiments of the TSS type, a large number of theoretical results indicated the need for a series of special experiments to refine various parameters of interaction between EDTs and the environment in accordance with the obtained theoretical data.

For carrying out repeated and sufficiently operational experimental studies, specialized spacecraft created for this purpose are most suitable. Requirements to reduce the cost of such experiments lead to the use of small tethered systems. The use of microsatellites and, in particular, the CubeSat's technology, can significantly reduce the cost of experimental research. For today, many countries are developing small EDTs projects on microsatellites and about a dozen of such systems have already been launched, but all these launches have failed.

The main reason for the failure of the experiments with small EDTs was the problems of emergency deployment of the tether. Therefore, for today, the basic principles of the theory of interaction of EDTs with the environment and its dynamics have not been sufficiently tested, and the need for orbital experimental data continues to be very high.

A series of interrelated orbital experiments with EDTs will allow us to formulate conditions for creating an effective removal system for spent spacecraft, and justify the choice of parameters of such a system for a specific spacecraft. In addition, the experimental data on the functioning of the EDTs are important for the creation of promising transport space systems based on the EDTs, operating in the mode of increasing the mechanical energy of the orbital motion due to the electrical energy of the system.

The report discusses possible schemes and technical solutions for carruing out orbital experiments with small EDTs on spacecraft developed by Yuzhnoye Design Office.

Electrodynamic Tethers as an Alternative to Current Orbital Station-Keeping Solutions

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Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

Electrodynamic tethers can provide propellantless propulsion by interacting with Earth's magnetic field. One major potential application of this effect is to replace the need for station-keeping propellant on spacecraft in Earth orbit. It has been proposed that systems ranging in size from CubeSats to space stations could benefit from using an EDT for station-keeping. This paper describes the results of a trade space analysis conducted to identify the range of missions which would benefit from the use of an EDT in place of conventional propulsion systems orbit maintenance. System mass, life-cycle cost, and mission risk were used as figures of merit for comparison.

Functions were developed to quantify each of these parameters for a range of spacecraft masses, ballistic coefficients, orbital altitudes, and targeted orbital lifespans with both EDT systems and conventional propulsion. Specific previous missions were used as examples and points comparison; data and requirements from these missions were used to constrain and guide the creation of the model. The results of this analysis indicated that EDTs for station-keeping are generally preferable for missions with longer targeted lifespans. The trade space model developed as part of this effort could be used by future missions to aid in determining whether including an EDT system would be beneficial.

Picosat/Femtosatellite Electrodynamic Tether Propulsion

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Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

The Miniature Tether Electrodynamic Experiment (MiTEE-1) is the first of two student CubeSat missions at the University of Michigan focused on demonstrating electrodynamic tether (EDT) propulsion for ultra-small satellites in the picosatellite (100 g–1 kg) and femtosatellite (<100 g) classes [1]. MiTEE-1 is scheduled to fly in 2019 on NASA's ELaNA-XX mission.

Picosat/Femtosat-sized spacecraft may enable the possibility of deploying large numbers for missions requiring a fleet of sensor spacecraft (e.g., distributed aperture, simultaneous spatial sampling). However, without propulsion these spacecraft would behave more as an uncontrolled *swarm* instead of a coordinated formation. Additionally, mission lifetime would be limited because of their high area-to-mass ratio. The work reported in [1] showed that a short (few meters to 10s of meters) EDT appears capable of providing propellantless drag cancellation and even the ability to change the orbit of picosatellites and femtosatellies over an altitude range in low Earth orbit (LEO).

MiTEE-1 seeks to confirm the current levels that are predicted to be collected by a femtosatellite end-body (approximately 2 × 6 × 6 cm) in LEO when biased to over a hundred volts positive [2]. This is done by deploying the end body on a fixed boom a distance of 1 meter away from the 3U main CubeSat body that emits electrons using a thermionic emitter. Measurements will be taken during both day and night as well as in high and low latitude conditions. MiTEE-1 also includes a Langmuir probe for obtaining measurements of ambient plasma conditions. MiTEE-2 will replace the fixed boom with a 10–30 m tether to deploy the end body.

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The relationship between the tension of the tether and the release speed and winding method.

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Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

The relation between the tension of the tether and the release speed and winding method during the release process of the tether is further studied through the ground experimental platform.

The rope release rate has an effect on both the maximum tension and the average tension, and is positively correlated at high speeds. At low speeds, the ropes are easily broken. The number of pulses is selected as 6400A and 12800A respectively, and the experimental results are shown in Figure 1 and Figure 2.

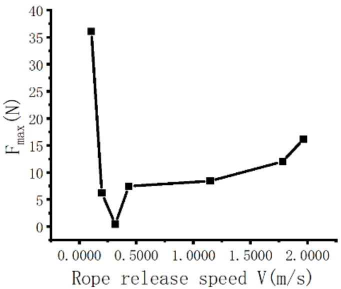

Figure 1. F_{max}-V（Pulse number 6400A）

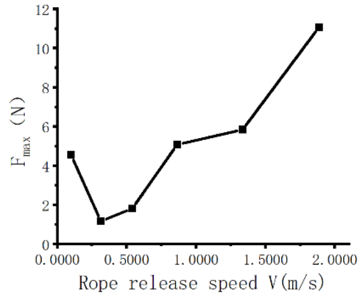

Figure 2. F_{max}-V（Pulse number 12800A）

The difference in winding method results in a change in the tension of the moving rope. When the rope is wound near the end of the motor, the tension value of the rope is relatively stable and less likely to break. And the more regular and tighter the winding, the more stable the tension is when the rope is released, and the less likely it is to break.

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Mission Analysis and Optimal Control for Cislunar Mission with Spinning Tether System in Hyperbolic Orbits

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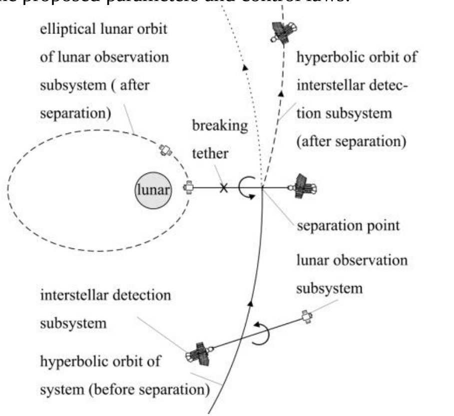
Conference Topic: Mission Concepts on Tethered Multiprobes

Spinning Tether System (STS) is one prospective application of tether satellite system. It provides a reusable and economic solution for orbit maneuvers, artificial gravity, space rendezvous, payload transfer etc. For deep space missions, it is assumable to assemble multiple functions within one spacecraft. However, it is difficult to refuel in deep-space, so separation and orbiting of individual modules requires energy savings as much as possible. Compared with conventional methods, through momentum exchange, STS can provide acceleration and deceleration maneuvers of different subsystems at the same time without or little fuel consumption, thereby maximizing fuel saving can be accomplished. In addition, STS provides controllable artificial gravity during flight.

This paper assumes one STS for deep space mission with one lunar observation subsystem and one interstellar detection subsystem. Two individual modules are assumed to be separated when the system flies to the moon (hyperbolic orbit). The lunar observation subsystem is assumed to be decelerated into one specific elliptical lunar orbit by tether rotation, and the other subsystem accelerated to achieve higher flight speeds. This paper proposes one assumed orbit for the proposed task background and analyzes the separation conditions of the system in accordance. The optimal control law is designed according to the proposed conditions to ensure that the system can be accelerated from the initial state to the desired rotation state, thereby achieving the final separation and orbital operation. Numerical simulations are presented and analyzed so as to verify the validity of the proposed parameters and control laws.



STS for deep space mission

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ESTCube-1

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Coulomb drag propulsion experiments of ESTCube-2 and FORESAIL-1

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Conference Topic: Tethers and Orbital Debris & Electric Sails for Interplanetary Exploration and Science.

ESTCube-2 is a three-unit CubeSat developed to a) Demonstrate effective deorbiting in low-Earth orbit with the plasma brake; and b) Demonstrate a platform which will be re-used on ESTCube-3 to test the electric sail in its authentic environment– the solar wind. Equally shaped FORESAIL-1 is hosting two scientific instruments and will perform technology demonstration of deorbiting employing similar system. Both nanosatellites make crucial steps for tether deployment and cost-effective deorbiting by the mean of Coulomb drag propulsion.

By charging the 300-m long tether with -1 kV, it is estimated that the 4-kg satellite will deorbit from 700- to 500-km altitude in half a year. The tether payload occupies less than one unit and weights around 0.55 kg.

The FORESAIL-1 nanosatellite is planned to be the first satellite to perform deorbiting and orbital maneuvers by propellantless propulsion. FORESAIL-1 is scheduled to be launched in 2020.

The ESTCube-2 satellite will also demonstrate systems required for electric-sail demonstration outside the Earth's magnetosphere: electron emitters, positive voltage source, reaction wheels, cold-gas propulsion, star tracker and deployable solar panels. The mission has been selected for European Commission's feasibility studies under the call for IOD/IOV experiments. If selected, the launch is expected in 2021.

This article will detail the payload design and elaborate on mission execution of plasma brake payload on cubesats.

The ESTCube-2 satellite is developed by Estonian Student Satellite Foundation and University of Tartu and the tether payload is provided by Finnish Meteorological Institute. Similar payload is hosted by the FORESAIL-1 satellite developed at Aalto University with the support of the Center of Excellence.

The RADSat-2 Tethered Cubesat Mission

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Conference Topic: Mission Concepts on Tethered Multiprobes.

In the early fall of 2022 *the sci_Zone team* will be flight testing and certifying the *LinkStar* global communications radio for multi-point/networked applications, and test tether technologies for cubesats on the *RADSat-2* satellite. The *RADSat-2* satellite is a 6U (60 cm x 10 cm x 10 cm) CubeSat that will be deployed from the International Space Station via the *NanoRacks* deployer. A key piece of this mission will be to fully test and demonstrate high speed full duplex communications with integrated GPS for tethered systems between the satellite and ground via the *Globalstar* satellite network utilizing the *LinkStar* radio architecture. *Globalstar* is a constellation of 32 satellites in LEO providing global data and voice services for a range of uses including oil rigs, shipping containers, gas pipelines and supporting remote communications. The mission will also be imaging the tether at either end to compare with other on board sesnors, and will support multispectral imaging of urban locations at night and large scale farming operations.

The *RADSat-2* satellite will separate into two 3U satellites connected by a 500m tether. Each 3U satellite will have its own *LinkStar* system which is comprised of a high speed duplex radio, simplex radio for global beaconing, GNSS for tracking and flight computer.

Each satellite will have an internet link allowing the cubesats to be nodes on the internet. Low resolution tether images, tether tension, position and flight performance data will be relayed from *RADSat-2* to the ground station via secure internet link to servers in our lab via the *Globalstar* network. One of the tethered cubesats will also host a hyperspectral camera to measure changes in urban lighting over time, and to image farm fields for a mínimum of four seasons.

In this briefing we will cover the *RADSat-2* mission including mission operations and tether deployment models. We will also discuss and demonstrate the *LinkStar* architecture and how it will be applied to *the RADSat-2* mission, including integration, networking, and ground operations via web based interfaces and the *QuickSAT* iOS app. Results from high altitude flights and lab testing will also be presented.

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Tether Attachment Point Stabilization of Noncooperative Debris Captured by a Tethered Space

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Conference Topic: Tethers and Orbital Debris

The tethered space system is treated as one of the most feasible approaches to handle with deorbiting space debris, for its higher security compared with other rigid capture methods. Due to the fact that the space debris is usually a noncooperative spacecraft, it might possess an unexpected attitude motion after capture. Therefore, it is preferred to stabilize the attitude motion of the debris before dragging the debris into the atmosphere or the graveyard orbit in order to avoid tether entanglement.

However, there are some obstacles for a tethered system to manipulate the attitude of the noncooperative debris. Firstly, the moment of inertia of the debris is unknown, thus its attitude motion is unpredictable and hard to be stabilized by a conventional feedback control law based on the observation of the attitude and attitude velocity of the debris. Besides, the tether tension is the only input in the attitude dynamic equation of the debris and it is required to be positive throughout to avoid tether slackness, which is similar to a saturation system. Only the value and direction of the tension are adjustable and the system is underactuated. Moreover, the length of the tether is usually relatively long, indicating a large-scale and rapid relative position manoeuvre of the mother satellite during a fast alteration of the tether direction, which might be unrealistic.

The way to stabilize the attitude of noncooperative space debris captured by a tethered space net system without any auxiliary mechanisms is discussed in this paper. The debris possesses unknown inertia information and status after capture while the tether tension is the only input to manipulate its attitude. The direction and value of the tension is regulated based on continuously dissipating the rotational energy of the debris. Moreover, the range of the direction of the tension is restricted in a small conical region in order to reduce the tether libration motion and the orbit manoeuvre of the mother satellite. The motion of the tether attachment point is desired to be observed instead of measuring the attitude motion of the debris in the feedback loop, which might be easier to attain in practical applications.

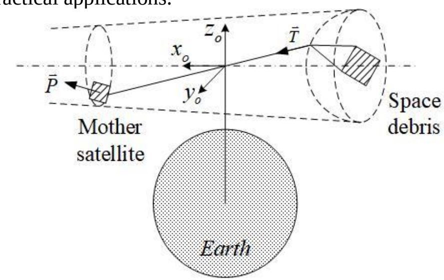

Illustration of a Tethered Space Net System Stabilizing the Attitude of Space Debris

Dynamics of a Debris Towing System with Hierarchical Tether Architecture

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Conference Topic: Tethers and Orbital Debris

Use of a tethered space-tug system has been recognized as one of the most promising techniques for space debris removal. Several studies of the dynamics of debris-tether-tug (DTT) systems can be found in the literature. If the debris has flexible appendages, the dynamic behaviour could be quite complex compared to that for rigid debris. Aslanov and Yudintsev [1] have considered a debris with flexible beams, and then examined the mutual interaction between the tether and beam. They also derived the critical tether stiffness for a given mass of space tug with which the DTT system undergoes large vibrations. The conclusions are very useful, but there is still more to be learnt for such systems. If the flexible appendages are panels, they should be modelled as plates, instead of beams. Furthermore, the system is likely to consist of multiple tethers similar to the system considered by Rui, et al. [2].

The primary goal of this paper is to study the coupled dynamics of a DTT system consisting of a debris with flexible appendages and multiple tethers as shown in Fig. 1. First, a 3D dynamic model of the DTT system is obtained using Kane's method in which the tug is regarded as a rigid body and while the debris has a central rigid body with flexible panels. The tether system, joining the two bodies, is attached to the tug at one end and then branches into multiple sub-tethers connecting to the edges of the flexible panels at the other ends. Elasticity as well as damping of the tether are included in the dynamical model. A lumped mass model is used for flexible panels. Only transverse displacements of the panels are considered because in-plane deformation is negligible. In order to extend this model to general cases, the number of sub-tethers as well as flexible panels is left arbitrary. The equations of motion are analyzed to determine the equilibrium points, stability behaviour and the oscillation frequencies of the system. This is followed by numerical simulations. Dynamic behaviour of the system with different initial conditions for the motion of the debris are studied as well as the case of flexible appendage breakage. It is concluded that the proposed configuration is able to stabilize the pitch and yaw motion of the debris.

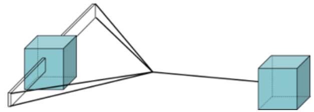

Figure 1 Geometry of the tethered space-tug system (*N*=2)

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The E.T.PACK Project: towards a fully passive and consumable-less deorbit kit based on low work-function tether technology

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Conference Topic: Tethers and Orbital Debris

E.T.PACK is a FET-OPEN project funded by the European Commission and aimed at the development of the first deorbit kit based on Low Work-function Tether (LWT) technology, i.e. a fully passive and electrically floating system made of a long conductive tape coated with a low work-function material. Thanks to the tether-to-plasma relative velocity and the presence of the ambient magnetic field, a tether segment captures electrons as a giant Langmuir probe and the complementary segment emits the electrons back to the plasma through thermionic [1] and photoelectric [2] effects. The LWT interacts passively with the environment (ambient plasma, magnetic field and solar radiation) to exchange momentum with the planet's magnetosphere, thus enabling spacecraft to de-orbit and/or re-boost without the need for consumables. This work presents the state-of-the-art of LWTs and the architecture and goals of E.T.PACK project.

The deorbit kit aims to reach Technology Readiness Level 4 and will have two modes of operation: as a fully passive LWT (nominal mode) and as a conventional electrodynamic tether equipped with an active hollow-cathode (backup mode). The low work-function material C12A7:e^- [3] will be applied to three elements of the kit: (i) the LWT itself, which needs the development of a new coating process, (ii) the hollow cathode for the backup mode, and (iii) a Photo Enhanced Thermionic Emission device [4] to convert solar photon energy into electrical energy. The kit will also include a control unit and a deployment mechanism compatible with the tribological properties of LWTs. Hardware components will pass through an intensive experimental and testing campaign to characterize thermal, mechanical, optical, and electrical properties as well as the resistance to ATOX and UV radiation. In parallel, theoretical studies on the interaction between LWTs with tape shape and the ambient plasma will be carried out and used to update LWT simulators. Such a work will create an envelope to determine the performance of LWTs in deorbit and re-boost missions.

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Model Predictive Tether-deployment for Precise Release of Tethered Reentry Body

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Conference Topic: Tethers and Orbital Debris

In the experiment of the YES2 mission, the re-entry body was released after the designed tether length had been deployed, but there were unpredicted errors in the conditions. As a result, it was admitted that the re-entry body may have come to Earth several thousand kilometres from the intended landing location and it was never found on the ground [1].

In this paper, we propose a model predictive control method for tether deployment that is intended to improve accuracy of landing. Our proposed method is not a simple tracking control scheme in which a single solution is determined for tether deployment to land at the target point; instead, a combined solution set, including solutions for landing near the target point, was determined. This model predictive control scheme incorporates the norm from the condition of the controlled system in the integration term of the objective function to the combined solution set at the release point. The unique advantage of this scheme is that the condition of the released re-entry body is generalized.

The effective of the proposed control scheme is demonstrated through numerical simulations in this paper. Figure 1 shows the results for the case of MPC. The along-track error does not depend on the initial tether length and angle errors and is reduced to within 300 km. These results show that the present MPC method is effective in controlling the tethered re-entry system such that the released re-entry body lands near the target point even if the initial tether state includes errors.

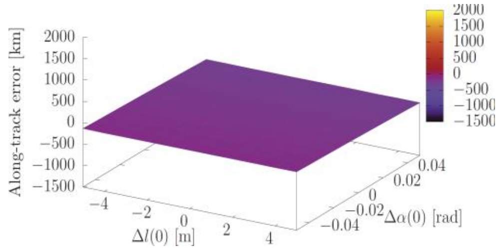

Figure 1. Results of along-track error under MPC

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Rate and collision probability of tethers and sails

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Conference Topic: Tethers and Orbital Debris.

The work done on probability of collision between spherical objects in orbit is extended here to the case of one spherical object and one rectangular object. Analytical formulae for the probability of collision as well as for the collision rate are obtained. The cases of fixed attitude and random attitude are considered. When the rectangular object is very elongated then some simplifications are possible. A numerical exploration of different scenarios is made.

This study is not tether-small debris collision, which has been done already, but rather tether-large debris or tether-spacecraft. This study was motivated and funded by the European Space Agency (ESA Contract No. 4000119560/17/F/MOS 'Environmental aspects of passive de-orbiting devices') because the ESA is interested in the impact of orbiting tethers on other, defunct or not, space craft.

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Collision Avoidance Capability of Gravity-Gradient-Stabilized Electrodynamic Tethers

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Conference Topic: Tethers and Orbital Debris

An electrodynamic tether (EDT) can effectively maneuver itself away from a predicted collision with a space object by switching on or off its current and controlling the (predominantly tangential) Lorentz force affecting its orbital evolution. However, a detailed analysis of the underlining collision avoidance dynamics has not been performed to date. Such an analysis is performed in the present work with the goal of assessing the maneuverability of an EDT when a collision is detected.

After showing that for a gravity gradient stabilyzed EDT can only benefit from a ζ-axis b-plane shift when avoiding a collision we model the achievable tangential acceleration magnitude accounting for its dependence on time as the EDT moves along the orbit and the achievable ζ-axis shift. We then relate the maneuver to the decrease in collision probability with a spherical object using a recent formula by Garcia-Pelayo et al. [1].

Preliminary conclusions show that km-size EDTs offer good maneuverability in Low Earth Orbit (LEO) to provide effective low-thrust collision avoidance even for last minute warning (half an orbit maneuver anticipation) except at the most problematic near-polar inclinations where at least one or two orbits maneuver anticipation is required.

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Novel Heaterless Low-Power Electron Emitters for Tether Applications

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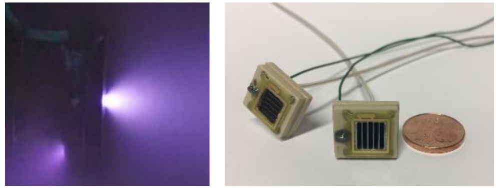
Conference Topic: Subsystem Technologies to Enable Space Tether Missions

Electron emitters are a crucial sub-system for electrodynamic tethers as well as for electric propulsion on spacecraft. We are developing a number of innovative low power electron emitter concepts for small satellites, which could be used on tether platforms too.

The first technology uses the new material called C12A7 as an insert for a hollow cathode that promises a low work function to emit currents at low temperatures. First prototypes were built and tested reaching several hundreds of hours for currents in the 0.1 A range using Argon as propellant. Contrary to other hollow cathodes, we do not need a heater to start operation, which greatly simplifies the overall architecture and reduces complexity and costs. The material may also be used for coating on aluminium tapes for passive electrodynamic tethers.

The second concept uses carbon nanotubes (CNTs) to emit electrons using field emission. Only a single DC high voltage source is required for currents of several hundred µA that was also tested for up to 500 h. We are presently trying to enlarge the array towards the mA current range. This CNT emitter will be used as the neutraliser for the NanoFEEP thruster on the UWE-4 satellite due to launch in December 2018. Applications towards CubeSat tether missions are also under evaluation.

Our presentation will summarise our efforts on novel heaterless electron emitters towards their first flight applications.



C12A7 Hollow Cathode and Carbon Nanotube Electron Emitters

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Analytical Deployment Control Law and its Experiment for a Tethered Satellite System

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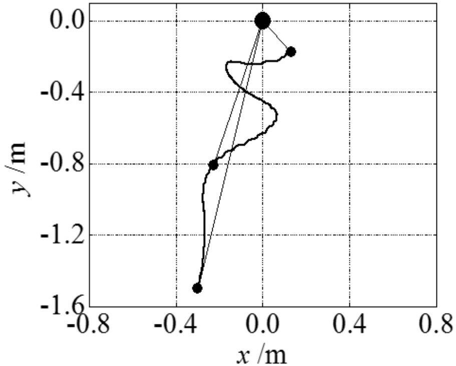
Conference Topic: Subsystem Technologies to Enable Space Tether Missions

Based on the nonlinear dynamic equations of a tethered satellite system, an analytical tether length rate control law for deployment is derived from the equilibrium positions of the system. The local and global stability of the proposed control law were theoretically proved via the Floquet theory and cell mapping method, respectively [1,2]. And, the parameter regions for stable deployment are obtained to maintain a tensile state of the tether during the deployment phase. Even if the system runs on a Keplerian elliptical orbit with a large eccentricity, the analytical control law is still applicable. Finally, a tether deployment subjected to an analytical control law in a ground-based experimental testbed is examined. A dynamics similarity is proposed for the ground-based experiment to reproduce the dynamic environment of the tether deployment of the on-orbit TSS. The experimental results show that the controlled tether is successfully deployed along an assigned direction under a taut state during the deployment phase [3].



Trajectory of satellite simulator

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Experimental Investigation of Tether Deployment Mechanism by Parabolic Flights

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Conference Topic: Subsystem Technologies to Enable Space Tether Missions

Tethered spacecraft system has numerous applications in space including power generation, attitude stabilization and de-orbiting the satellite at the end of its mission. A common and critical requirement for all tethered missions is that the tether should be fully deployed and stabilized in the desired orientation. Past decades have witnessed 27 orbital and suborbital tether missions flew with limited success. Many of them failed prematurely due to ENGINEERING problems not scientific principles. Among all failures, the failure in deploying tether from the spacecraft is the most common, e.g., the MAST mission [1] in 2007 where only 1m out of 1km tether was deployed, the KUKAI mission [2] in 2009 where only a few centimeters out of 5m tether was deployed. The latest failure is the JAXA' electrodynamic tether mission in early 2017 where the tether didn't deploy at all [3]. Although it is not possible to completely eliminate the possibility of mechanical failure of the deployment and stabilization mechanism, a thorough experimental verification of the behaviour of the tether deployment system, given the mission parameters, is a must in order to ensure a successfyl and complete deployment of the tether in space. This paper reports an experimental validation of a tether deployment system using two 1U cubesats by parabolic flights.

Macroscopic Hollow Cathode Modelling: A Variable-Separation Approach

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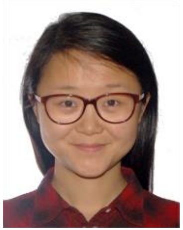

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Conference Topic: Electrodynamic and Momentum Exchange Tether Propulsion

The concept of electrodynamnic tether system evolves together with its dependence on Hollow Cathode (HC) performance. The bare tether carries no insulation and collects electrons along the tether itself, thus being able to significantly improve anodic contact, compared with that of giant spherical contactor at tether end [1]. The efficiency of bare tether requires HC to be able to emit all collected electrons at a negligible potential drop. It was found that a non-negligible potential drop would strongly deteriorate the deorbit performance, specially for a tether less than a few hundred meters long [2]. Apart from their crucial role in tether applications, HC technologies - providing electrons both for discharge chamber and beam neutralization - are also critical for modern electron-discharge ion thrusters. For this reason, as a prerequisite to design efficient and durable HCs, physics of HC needs to be studied and important mechanism beneath operations demands to be understood. With the goal to aid HC design, this work develops a two-dimensional, axisymmetric, and variable-separation fluid model to study the plasma dynamics of HC. By using an approximate variable-separation technique (successfully applied to Hall thruster [3] and Helicon thruster [4]), the radial and axial dynamics can be partially decoupled, with local wall-contact frequencies as main coupling parameters. Current balance is studied to evaluate the discharge capability of the cathode. Energy balance includes the power conversion between ions and electrons, ionization losses, wall losses/gains, et cetera. Taking advantage of the simplicity of this partially-decoupled model, parametric analyses can be performed to study the influence of principle parameters (for instance, insert properties and cathode geometry) on cathode performance.

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Tether Deployer for Electric Sail Validation Mission

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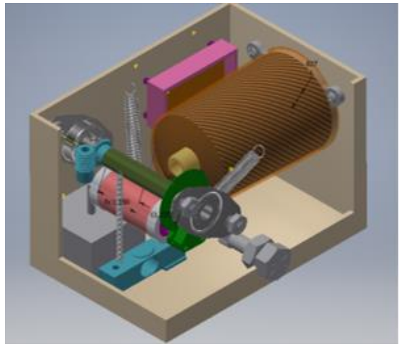
Conference Topic: Subsystem Technologies to Enable Space Tether Missions

Electric sails take advantage of one of the most basic engineering concepts, conduction. An electric sail is a concept in which long, thin, conductive wires propel a satellite through space by repelling the protons found in solar wind. Theoretically, this design could allow for faster (400 – 700 kilometers per second) and farther space travel than ever before, without any kind of material propellant. Because the length of tether required to achieve these speeds can be several kilometers long, a tether deployer is needed. Currently, a concept validation mission is being planned for this kind of design. The satellite system will consist of two satellites with 16 kilometers of tether between them. Cold gas thrusters will be used to spin the satellites around one another, creating a centripetal force on the system which will pull the tether into tension between the satellites. While spinning, the tether will deploy from both satellites. A tether deployer of this nature has been designed and prototyped by a team of engineering students at the University of Kentucky. The deployer is capable of holding eight kilometers of tether, and deploying and braking the tether all without using Earth's gravity. Inside of the deployer, a system of pinch rollers, gears, and a stepper motor controls the speed of deployment. The tether will be professionally wound using a textile manufacturer and deploys from a fixed spindle in the rear of the deployer. An Arduino Nano receives all tension, speed and length data from a tension sensor and optical encoder and uses this data to control the motor. The design stage of this project is complete and will soon be taken to NASA Marshall Space Flight Center to be tested on a flat floor. The test will consist of a single deployer, rotating around a hub on air bearings to induce a frictionless motion. Braking will be tested using the motor and pinch rollers, as well as the counting system and integrity of the system. The engineering team at the University of Kentucky expects to successfully complete testing, as intense analytical work has been done to ensure that the system is overdesigned for specifications.



Survey of Tether Deployment Mechanisms for Use on a Barbell Electric Sail

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Conference Topic: Subsystem Technologies to Enable Space Tether Missions

z Sail (E-Sail) is a novel type of deep space propulsion which utilizes a positively charged tether to interact with the solar wind and propel the satellite forward [1]. The E-Sail is envisioned to deploy multiple > 1 km tethers. Deploying these tethers in deep space means that a gravity gradient cannot be used to deploy and/or stabilize the deployment. As such, thrusters or some type of braking mechanism must be used to slow the deployment of the satellites.

The paper here seeks to investigate past successful and unsuccessful tether deployment missions. A comprehensive review of tether missions was done in 2013 by Yi et al [2].

An example braking mechanism has been created at the Facility for Aerial Systems and Technology (FAST) and tests have been done to characterize the braking force attained from the device as shown in the Figure. The braking mechanism designed uses two sinusoidal plates. The plates separate and allow the tether to pass through the plate. The plate separation varies and increases friction on the tether.

Future work will be done on characterizing the friction characteristics of different braking mechanisms.

Promise is shown in using an Electromagnet to slow rotation of a tether wrapped around a spool.

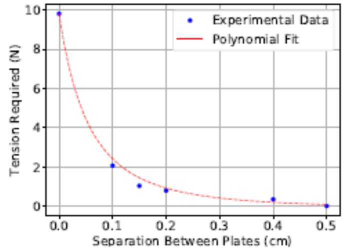

Fig. 1. Braking Test Experimental Results

The goal of a E-Sail braking mechanism is to reduce residual axial vibration by reducing the amount of residual energy in the system. Previous work has been published in a NASA technical note [3].

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Parameters Impacting Ion Emission from a Contactor Plasma

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Conference Topic: Subsystem Technologies to Enable Space Tether Missions

Enhancing tether current is critical for electrodynamic tether propulsion applications. Plasma contactors that produce a high density, quasi-neutral plasma have been used for this purpose, primarily by enhancing electron collection from the ambient plasma. This electron collection process has been the subject of targeted research, while the complementary ion emission process has been largely ignored in comparison. As a result, electrodynamic tether use has not been possible in tenuous plasma regions such as Mercury, interplanetary space, and Earth's outer magnetosphere. In these regions, electron collection is insufficient and ion emission is the only viable option. Thus further research on the ion emission process is required to enable this class of tether-based propulsion.

A series of parametric chamber experiments were completed to address how ion emission from a contactor plasma may scale in tenuous space plasmas. Experiments focus on how spacecraft potential scales with electron emission current (from the other side of the tether), contactor current (the rate at which the contactor generates quasi-neutral plasma), and contactor expellant mass (ion mass). These experimental results are compared to scaling laws derived via Curvilinear Particle-In-Cell (CPIC) simulations for further validation and physical insights [1,2]. Ongoing scaling experiments with an axial magnetic field are presented as an external field is critical for electrodynamic tether applications. Implications for improving space plasma measurements and enabling future tether experiments are discussed.

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De-spin of Massive Rotating Space Object by Tethered Spacecraft

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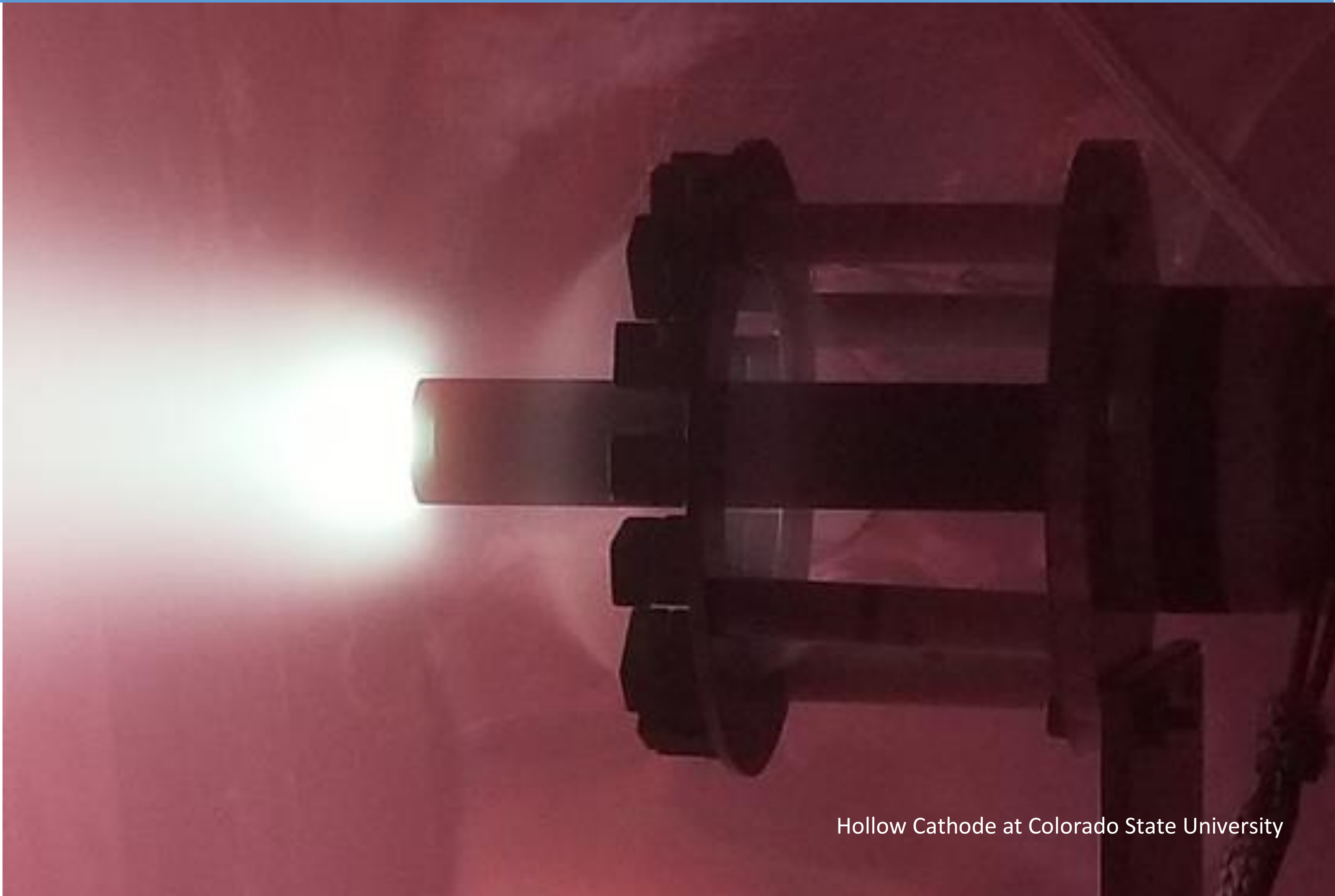
Conference Topic: Subsystem Technologies to Enable Space Tether Missions

It is essential to implement the debris removal and asteroid redirection by the reason of the potential hazards of the debris and asteroid on space safety. Many technologies have been proposed for such tasks, such as tethered space robotics, space net and gripper mechanism. One significant challenge of such technologies is that in fact, the object (asteroid or space debris) are likely to be rotating after capture that may pose a problem for operation.

In this paper, the authors focus on the dynamics and control of de-spin a large space object by a small tethered system in the post-capture phase. The dimensionless dynamic model of the tethered space tug system is established, and three different de-spin control strategies are developed, such as thrust control, tether tension control, and the combination of both. The de-spin by thrust control uses the thrust at a small space tug, while the de-spin by tension control is achieved by regulating the tether length to dissipate the rotating kinetic energy of the object without consumption of propellant. The combination of both control strategies is to achieve the de-spin using less propellant.

Numerical simulations are used to compare and show the effectiveness that large rotating object could be de-spun through a small tethered tug with limited thrust in a finite time by the thrust at the tug, adjusting the tether length, or the combination of both.


Hollow Cathode at Colorado State University

Effects of Critical dimensions on discharge characteristics in low-current hollow cathode contactors

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Conference Topic: Subsystem Technologies to Enable Space Tether Missions

The relations between key dimensions of the low-current (1.5A) hollow cathode plasma contactor (HCPC) and its discharge performance have been investigated.

An empirical equation on the effects of the pressure on the insert effective length inside the cathode has been reported by [1]:

$$p \cdot L_{effective} = K, K = 5 \sim 15\,\mathrm{m \cdot Pa}\,.$$

The effective length of the emitter is defined as the part where the total current flux ($\mathbf{j} = \mathbf{j}_{\mathrm{emission}} + \mathbf{j}_{\mathrm{absorb}}$) is in the same direction of the emission current density $\mathbf{j}_{\mathrm{emission}}$. With a 2-d fluid plasma code, the influence on the insert effective length of the internal pressure in a low-current HCPC has been studied. The emission current flux governed by the Richardson-Dushman equation and the absorbed current of electrons and ions on the emitter inner surface governed by the insert plasma parameters (T_e, T, n, *etc*.) have been considered.

Kaufman presented a statistical regulation [2] on the discharge stability, that the hollow cathodes worked in the spot mode when ratio of the propellant flow in ampere and the orifice diameter was higher than 0.27 A/mm

$$J_{propellant} / d_o \geq 0.27 \text{ A/mm}\,.$$

The effect on the discharge stability of the orifice diameter has been researched. And the diagnostic method has been expanded to the emission probe (Figure 1).

The mentioned empirical equations were based on the high-current hollow cathodes (≥3A). Therefore, the validity has been verified and revised for a low-current HCPC, of which the nominal current is 1.5A. And the physical mechanism has been preliminarily discussed.

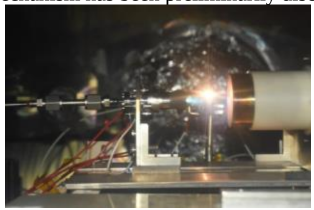

Figure 1. A working emission probe

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The Dynamics and Stabilization of a Moon-based Space Elevator

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Conference Topic: Space Elevators

This paper proposes a new space elevator application named the moon-based space elevator. The moon-based space elevator is a partial space elevator in which an end body is connected to the moon by tether. One or multiple climber(s) can move along the tether to transfer the cargo between the moon and the end body. The dynamic characteristics of the moon-based space elevator are studied using a multi-piece dumbbell model. It is found that the control tensions in tethers should be considered to avoid slacking. This increase the difficulty for the transfer stabilization. Thus, mission strategies are proposed to stabilize the libration of the climber(s) and the end body in the transfer period based on the dynamic characteristics. Optimal control is employed to regulate the motion of the climber(s) in different transfer phases. The effectiveness of the proposed strategies is demonstrated by numerical simulation. Simulation results show that the newly proposed strategies stabilize the motion of the moon-based space elevator in the orbital transfer period effectively.

Space Experimental Results of STARS-C;
CubeSat for Verification of Tether Deployment in Orbit

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Conference Topic: Space Elevators

Our group are trying to verify the technology of space elevator by using Microsatellites and obtain data for future design. Our first trial was STARS-C [1], [2]. The purpose of the STARS-C is to demonstrate smooth deployment of a tether in space and to obtain the tether dynamics data for future design of tether deploying systems. It is 2U in size. It consists of a mother satellite (MS) and a daughter satellite (DS), and is designed to deploy a 100-m tether between them composed of aramid fiber between them. The MS and DS have common subsystems, including power, communication, and command and data handling systems. They also have a tether unit with spool and reel mechanisms as a mission system and solar paddles with antennas. Figure 1 is the image of STARS-C.

STARS-C was launched on December 9 in 2016, then released from JSSOD on December 19 in 2016 (Fig.6), and was operated until its re-entry on March 2 in 2018.

Unfortunately, the detail data could not be obtained because the condition of transmission was not good. However, we succeeded the optical detection of STARS-C from the ground supported by JAPOS, and also could be determined that a part of tether was deployed from the data of tie variation of STARS-C altitude and the satellite condition. We also found that the coiling effect of tether had a negative large effect on the deployment of tether from these data and the additional ground experiment.

The detail results will be shown in the conference.

Figure 1 Image of STARS-C.

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Energy and Orbital Stability in Deploying the Earth Space Elevator

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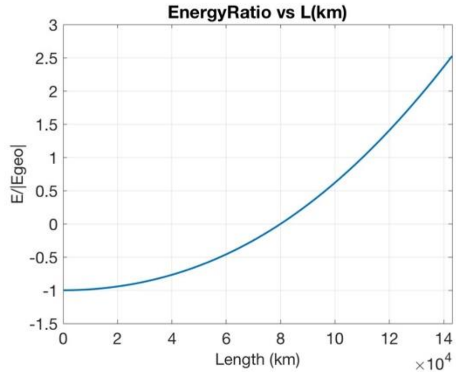
Conference Topic: Space Elevators

The Earth Space Elevator [1] is an ingenious concept aimed at providing easy access to space, eliminating the need for rockets and potentially reducing drastically the launch costs. Well known issues, among others, that can make the Space Elevator possible are the availability of new and super-strong tether materials (i.e., with a high ratio of yield strength to density) and the survivability of the tether to impacts of micrometeoroids and orbital debris. Various aspects of the dynamics and stability of the elevator have also been analysed by other authors particularly for the case of a space elevator anchored to the ground.

This paper aims at addressing issues related to the orbital energy of the system when the elevator is being deployed starting from a nucleus in geostationary orbit (GEO). The energy increase needed to keep the orbital centre, where the forces balance out, at GEO altitude during assembly while the tether is lengthened leads to a circular orbit with a positive orbital energy [2], i.e., the closed orbit has an energy level pertaining to a hyperbolic orbit. This situation leads to the instability of the unanchored system that would tend to escape from the geostationary orbit.

The paper illustrates the change in energy during assembly for systems using either cylindrical (see Figure) or tapered tethers and investigate the parameters that need to be controlled for maintaining the system on the geostationary orbit before anchoring.



Energy/|Egeo| vs length for a massive cylindrical tether with orbital centre at GEO altitude. The length of 144000 km pertains to a fully-deployed system with the lower tip touching the Earth's surface.

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Parametric Study of Partial Space Elevator System with Simultaneous Operation of Multiple climbers

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Conference Topic: Space Elevators

This paper studies the dynamics of a partial space elevator (PSE) system with multiple climbers based on the nodal position finite element method in the arbitrary Lagrangian-Eulerian Framework. In this model, the inertia of tether, the elasticity and flexibility of tether are considered. In current work, the PSE system contains a main satellite, intermediate satellite, sub satellite, and flexible tether connecting them together. Firstly, the effect of realistic gravitational model influence on the dynamics of PSE system is investigated. After that, the effect of the flexibility of tether influence on the dynamics of PSE is investigated in two different cases. It is found that the higher-order frequency oscillation of tether cannot ignored when the mass of tether cannot ignored. In addition, it is found that the simultaneous operation of climbers changes the position of centre of mass of PSE system significantly. Therefore, it affects the orbital dynamics of PSE system. Based on these results, a systematic parametric analysis is conducted for the PSE system. To convenience the study, two mass ratios for the PSE system have been defined. During the parametric study, the effects of mass ratios, operation procedure of two climbers, and velocity profile of climber influence on the dynamic behaviour of PSE system are investigated. This parametric analysis is helpful for the design of a PSE system and engineering application of the payload transportation using PSE system.

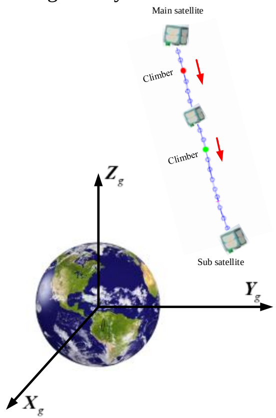

Figure 1 Schematic of Partial Space Elevator System with multiple climbers

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Effects of a Climber's Motion on a Tethered Cubesat System

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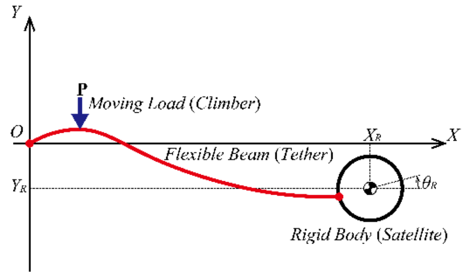
Conference Topic: Space Elevators

Tethers are a mechanical element that have excellent light-weight and compactability properties, that allow for simpler construction of large-scale systems. There have been many uses proposed for such tethered systems, with one proposal being that of an in-orbit payload transfer system. This system utilizes a mechanism called a climber to move along a tether deployed in space to transfer payloads to higher orbits; and is also known as a partial space elevator. There has been a Cubesat launched to prove the technological feasibility of this idea, but the tether length is very short, so there is a need to establish various technological elements for the realization of a large-scale system. This is an important topic, especially when considering how to avoid collision with other surrounding spacecraft during an in-orbit proof of concept experiment. However, as the tether is a soft-body, there will likely be large positional drifts and deformation, as well as residual vibrations from the climber travelling along the tether, which result in complex behavior. Thus, this research aims to develop a numerical analytical model that can be used to analyze the motion of such a system; with the first step being an investigation of such a system's two-dimensional motion. The system is defined as having a moving mass, with a flexible beam held at one end; and the ANC method is applied to the creation of formulae which are used to perform a numerical analysis. Furthermore, the results of the simulation will be compared to those of a basic mock-up experiment, for verification purposes.



Analytical model

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Tethers for Lunar Development

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Conference Topic: Space Elevators

In light of recent industry initiatives to create a Moon economy, this paper explores the feasibility of a Moon based space elevator or large space tether system in orbit around the Moon, using present or near-future technologies and construction methods. This paper presents the results of an analysis of systems of various tether lengths and for end masses of different size and location. The paper also discusses a number of non-technical topics, like policy and international relations. The potential impact of selected possible system configurations on the moon economy is evaluated through the use of example theoretical case-studies, restricted to the parameters of interest.

Resulting tether parameters like length and tether strength are then contrasted against existing estimations in literature of corresponding attributes of Earth-based systems, aiming to evaluate the relative feasibility in the two environment and determine if a Moon mission would serve as a representative proof of concept for an Earth based system. Such a proof of concept could reduce the time to maturity of tether capabilities through the testing of technologies required and their potential earlier operational verification (e.g. collision avoidance, recovery, and consequences).

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Fixed-time terminal sliding mode control of spinning tether system for artificial gravity environment in high eccentricity orbit

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Conference Topic: Tethers for Artificial Gravity

In this paper a new method is introduced to produce the artificial gravity environment by spinning tether system(STS) in high eccentricity transfer orbit. Compared with other common artificial gravity environment methods, spinning tether system has simple structure, light weight and suitable spin velocity, which is more favorable for the spacecraft to generate the artificial gravity in the weightless space. Kirk Sorensen mentioned two kinds of spin schemes in the process of generating artificial gravity by spinning tether system in his research paper [1], including Constant Moment-of-Inertia,Variable Angular Momentum (propulsive maneuvers to change angular rate) and Constant Angular Momentum, Variable Moment-of-Inertia (tether reeling to change angular rate).

Deployment of tether and spin up processes are carried out step by step in the both schemes, and there are disadvantages of long start-up time or high energy consumption obviously. Therefore, the mathematical model of the spinning tether system is established by the second type of Lagrangian equation firstly. Then, the tension control law and the tangential thrust control law of tether system are designed. Through the mutual coordination of both control law, a method of Variable Moment-of-Inertia and Angular Momentum is realized which makes the tether system spin along the expected spinning velocity in most of the processes of uniform development by stable tangential thrust. With the end of development, the artificial gravity environment level on the spacecraft also met the expected requirements, and the tether system open loop trajectory curve under the high-eccentricity transfer orbit was obtained. Finally, considering the rapidity of convergence time, a fixed time terminal sliding mode controller is designed to control the closed-loop trajectory curve of the tether system.

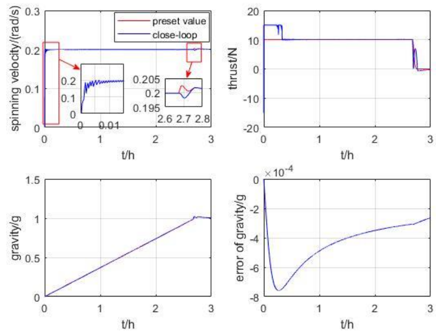

Figure 1 time histories of angular velocity, artificial gravity and thrust

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Inflated Tubular Tethers for Partial Gravity Facilities

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Conference Topic: Tethers for Artificial Gravity

Figure 1 shows a most remarkable feature of our solar system: its tight clustering of surface gravity levels.

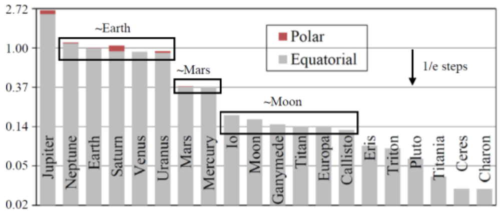

Figure 1. Clustering of Surface Gravity in our Solar System

Four planets beyond earth have nearly earth gravity. But Venus, Saturn, Neptune, and Uranus are not promising for early human settlements. Mars (and a few places on Mercury) are more viable. And the 5 other large solar system moons all have nearly our moon's gravity.

Sustained microgravity has uncovered a wide range of human health challenges not seen in earth gravity. But our only partial gravity health data is from 1-3 day lunar stays on Apollo. That was far too short to have evaluated health issues identified only later, after months of microgravity.

Rather than spending months on the Moon or Mars to test the health impacts of partial gravity, we can evaluate human health in Moon and Mars gravity in low earth orbit. A long slowly-rotating asymmetrical dumbbell in low orbit can provide Mars gravity at the lighter end and Moon gravity at the heavier end, as shown in Figure 2:

Figure 2. Rotating Dumbbell for Partial Gravity Tests in LEO

I presented this at the 2016 tether conference.[1] The focus of this paper is to present a detailed design and analysis of an inflated tubular tether for such a facility.

The obvious function of this tether is to reliably hold the Moon and Mars "gravity nodes" together despite high centrifugal loads and repeated debris impacts. Using a wide enough inflated tube can also allow "shirtsleeve" crew plus cargo transfer between nodes with different gravity levels. Other useful roles also seem possible, including thermal management and highly automated crop growth plus air revitalization.

This paper covers these topics, plus MMOD impact avoidance, shielding, detection, and repair. The paper also discusses NASA's TransHab inflatable space structure patent,[2] which has several features that might be usefully incorporated into this inflated tube.

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Rotation Deployment Strategies and Sliding Mode Control of Hub-Spoke Tethered Satellite Formation System

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Conference Topic: Formation Flying and Enabled Missions

The stable deployment in Earth orbit is one of the key technique difficulties for Tethered Satellite Formation System (TSFS), which is the premise of TSFS missions, such as Earth observation and interferometry measurement. Since the model of TSFS has the properties of strong nonlinear and tight coupling, the deployment control is always a key topic both in control theory and space experiment. The Hub-Spoke Tethered Satellite Formation System (HS-TSFS) has good application prospect in the field of multi-point measurements, which formation configuration stability is guaranteed with rotation in orbital plane [1]. However, the rotation motion increases the dynamical complexity of deployment [2]. This paper addresses the deployment control strategies for TSFS with hub-spoke type, which corresponding controllers are designed by Sliding Mode Control (SMC) theory respectively.

The model of HS-TSFS is derived by Lagrange Equations with considering the attitude motion of the central satellite in a circle orbital plane firstly. The rotation deployment characteristics are investigated under numerical simulation that declares the existing problems during deployment stage, for instance, the saturation of control inputs and rotation rate variation. After that, two deployment control strategies of HS-TSFS are proposed based on tension control and tension thrust hybrid control. For the tether tension deployment strategy, which is a typical under-actuation process, the central satellite attitude controller and deployment tension controller are designed separately for simplifications. The tension controller is presented by under-actuation SMC with tension saturation considered. In order to enhance the deployment accuracy and anti-interference ability, the tension thrust hybrid strategy is proposed. The controller for this strategy is presented to realize the central satellite rotation and sub-satellite deployment in the same time. For completing the deployment process of HS-TSFS in finite time, a terminal sliding mode control (TSMC) is presented for rotation deployment with considering tether tension and thrust saturations. Finally, the system stability under proposed controllers is proved based on Lyapunov theory. And several numerical simulations are performed to illustrate the effectiveness of proposed controllers to deploy HS-TSFS in orbit.

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Dynamics of a tethered satellite formation for space exploration modeled via ANCF

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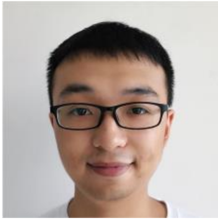

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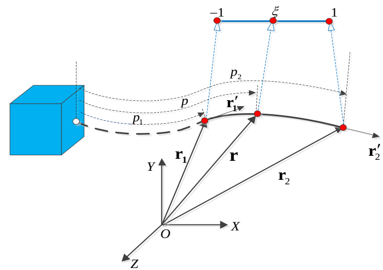
Conference Topic: Formation Flying and Enabled Missions

This paper studies the dynamics of a spinning three-body tethered satellite formation by a flexible multibody dynamics method. The tethered system is specially designed to constitute a Space Infrared Interferometric Telescope for a space exploration mission [1]. The sub-satellites are deployed from the main-satellite using long flexible tethers and moving along trajectories of Archimedes spirals with a constant angular velocity. Both of the large displacement and deformation of the variable-length tethers are described by utilizing the Absolute Nodal Coordinate Formulation (ANCF) method in a framework of Arbitrary-Lagrange-Euler description [2], while the Natural Coordinate Formulation (NCF) method is used for describing the overall motions of three satellites. Considering the mass flow of tether element, the governing equations of tethers with different physical properties are derived by using the d'Alembert's principle. The coupled dynamics equations of the system are obtained with a method of Lagrange multipliers. Numerical case studies are presented for performing a basic validation of the realistic engineering system by comparisons in terms of different system parameters.



Dynamics model in ANCF

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LinkStar: A Radio/GPS/Flight System for multi-point networking of Formation Flying Small Satellites and Tethered Satellites

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Conference Topic: Formation Flying and Enabled Mission

LinkStar, is a low cost and secure satellite based radio-gps-flight system for a range of small satellites. For low Earth Orbit operations, the LinkStar architecture treats the radio system as a secure node on the internet through the *GlobalStar* satellite communications network. The communications component is comprised of either a high speed duplex (concurrent uplink and downlink) link and/or a simplex beaconing link. The duplex component provides communications coverage to over 50% of the Earth at data rates of up to 256kbps. The duplex modules treats the vehicle as a secure node on the internet while the vehicle is in orbit allowing for multi-network, integrated communications. The simplex beaconing unit allows for messages of up to 144 bytes and provides nearly 100% coverage in LEO. Commuications from both modules is through the *Globalstar* satellite network, which has 32 satellites in LEO that are linked to ground stations through out the globe. Research focused on integrating these communications modules with the *NovAtel OEM 719 GNSS*, a modified *Beagle Black* computer, and the *QuickSAT/Vehicle Management System (VMS)*. Test results show the *OEM 719* with "COCOM Limits" removed (speed and altitude) with proper antenna integration will provide position acquisition within 4-6 minutes to an accuracy of less than 1m. When combined with the *LinkStar* simplex module, the location, heading and speed of the small satellite system or satellite in a tethered architecture will be communicated to the ground from anywhere in orbit. The results of the GNSS/Comm test will be presented.

QuickSAT/VMS is a flexible open source flight management system tailored for cubesats and other types of small satellites. The architecture provides for basic vehicle command and control, data management, scheduling, event handling and a complete software based radio tool set. The framework allows for users to define custom classes of components (such as GPS, radios, magnetometers and other sensors) without modifying the core architecture. The architecture provides a robust data management architecture, not only managing the vehicle configuration and schedule, but also logging system messages, errors and events, and storing data as needed into separate recording sessions. *QuickSAT/VMS* also has a matching ground based web application and iOS app allowing for vehicle TT&C, and multi-satellite networking.

In this briefing we will discuss the core features of the *LinkStar* radio architecture and related research, the *QuickSAT/VMS* open source software architecture, discuss how users can integrate *LinkStar* with their satellite, discuss near term missions, and briefly demonstrate its use.

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Three-Dimensional Tethered Slingshot Maneuver in the Elliptic Restricted Problem

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Conference Topic: Other advanced tether concepts.

A possible technique to maneuver a spacecraft in space is the Tethered Slingshot maneuver (TSSM) [1-3]. The spacecraft approaches the body, connects to the tether, rotates around the body by a given angle and disconnects from the cable to follow its trajectory. The rotation in the tether changes the parameters of the maneuver, giving or removing energy to make the spacecraft to reach goals that would be too expensive, relative to fuel consumption, for a standard maneuver based only in propulsion systems.

The space tether configuration consists in a cable attached to the surface of a celestial body and the other end having a device that will connect to the spacecraft for the maneuver. The cable is considered thin, rigid, inextensible and with negligible mass.

Previous work presented the maneuver for the capture of a spacecraft, considering the circular and plane case [3], and others considering the three-dimensional space and systems in circular orbits [4].

This work proposes to study the maneuver developed in three-dimensional space and around a system of bodies in elliptical orbit. The paper concentrates in the astrodynamics aspects of the maneuver, to show the benefits that a maneuver of this type can give in terms of modifying the orbit of the spacecraft.

The analyses of the energy variation and/or inclination in the orbit of the spacecraft around the main body of the system will be made. Different conditions for the geometries, sizes and locations of the tether will be considered to make general maps of the solutions. These maps can serve as a guide to possible missions.

The results will show the best location to place the tether, as well as the best moment for the close approach, in terms of the relative position of the tether and the spacecraft in the moment of the closest approach.

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Tether capture of spacecraft at Neptune

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POLITÉCNICA

Conference Topic: Other Advanced Tether Concepts

Uranus and Neptune are considered flagship missions. For minor missions, tethers could provide free propulsion and power for capture and exploration at an Ice Giant. Its magnetic field B exerts Lorentz drag on tether current driven by the motional field Eind, itself proportional to B, capture efficiency (S/C-to-tether mass ratio) going down as B2 for weak fields. For Jupiter, efficiency is reduced by its very intense B, limiting tether length to keep current density well below its maximum, short-circuit value σcond Eind, to avoid strong tether heating, and energetic attracted electrons missing collection by a thin tape; this does not apply for weaker B, capture efficiency being comparable for Jupiter and Saturn [1].Tether operation depends on plasma density, but data from the Voyager 2 flyby [2] did not yield definite model of the magnetized plasma the tether would be operating in at Neptune. However, for reasonable density values, appropriate and reasonable tether lengths lead to length-averaged tether current near the short-circuit maximum, which is independent of actual plasma density. Field B is due to currents in some small volume inside the planet. The field outside is described through the magnetic-moment vector and the dipole law approximation, decreasing as inverse cube-power of distance, 1/ρ3. For Saturn, and roughly so for Jupiter, the dipole is at the planet center and parallel to its rotation axis. The Neptune case is more complex. Quadrupole and octupole terms and/or differently localized current sources might need be considered, but the dipole dominates capture. Most relevant features in Neptune environment are large dipole offset, 0.55RN, and tilt, 47°, with respect to the rotation axis. Efficiency calculation will use the detailed OTD2 dipole model [2]: location 0.19RN below the equatorial plane and 0.52RN radially away from the axis, and tilt orientation such that it is inclined 22○ with respect to the meridian plane of the dipole. Lorentz drag, decreasing as 1/ρ6 with distance, requires periapsis very close to the planet [1], rp ≈ RN ≈ 25000 km; drag takes eccentricity from just above 1 to just below 1, orbit keeping near parabolic through capture. Because of the strong offset, the S/C should best reach periapsis near its crossing the meridian plane of the dipole center; this synchronism is eased by Neptune having, among Giants, high density (making for fast orbital motion and capture) and slow spin.

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Tethered spacecraft charging mitigation for space experiments with electron beams

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Conference Topic: Other Advanced Tether Concepts

The recent development of compact, relativistic, electron accelerators might open up a new era of active experiments in space, driven by important scientific and national security applications. Examples include using electron beams to trace magnetic field lines and establish causality between physical processes occurring in the magnetosphere and their image in the ionosphere [1-2]. Another example is the use of electron beams to trigger waves which could induce pitch-angle scattering and precipitation of energetic electrons, acting as an effective radiation belt remediation scheme [3].

High-power electron beams operating in the low-density magnetosphere require a spacecraft-charging mitigation scheme to prevent catastrophic charge build on the spacecraft. One possible solution has been recently proposed by Delzanno et al. [4]. It is based on the plasma contactor, i.e. a high-density neutral plasma emitted prior to and with the electron beam, which compensates for the electron beam current by emitting substantial ion currents.

We present here a possible alternative. It consists of attaching a large passive conducting surface to the spacecraft, a "tethered capacitor", from which negative charges would be drawn to compensate for those lost from the electron beam. This concept is explored using three dimensional Particle-In-Cell (PIC) simulations from which scaling laws can be inferred for the spacecraft and tethered capacitor potentials under proposed electron beam operations. Although somewhat idealized, the simulation results suggest that the proposed approach is viable [5].

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Optimal trajectories of electric sail with uncertainties

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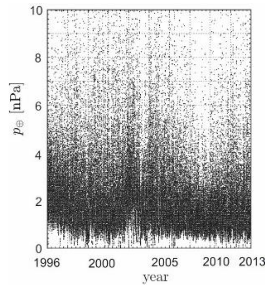
Conference Topic: Electric Sails for Interplanetary Exploration and Science

An Electric Solar Wind Sail (E-sail) is an innovative propulsion system that needs no propellant to obtain a propulsive acceleration, because the thrust is generated by exchanging momentum with the solar wind charged particles. The E-sail (heliocentric) trajectory is usually analysed in an optimal framework by looking for the optimal control law that minimizes the total time of flight required to reach a target celestial body; see Ref. [1].
In a preliminary mission analysis, the E-sail thrust is usually modelled by considering average values of the solar wind characteristics. Actually, the solar wind properties are subject to non-negligible variations over time. For example, the figure below shows the hourly variation of the solar wind dynamic pressure at a Sun distance of 1 au, from January 1996 to September 2013. These data suggest that the E-sail propulsive acceleration should be studied as a stochastic variable rather than a deterministic one, as is discussed in the work by Niccolai et al. [2]. In a recent study, Greco et al. [3] have developed a tool able to solve optimal control problems under uncertainties by introducing a stochastic multiple-shooting transcription method. Using an approach similar to that described in Ref. [3], the aim of this work is to analyse the E-sail-based optimal transfers taking into account solar dynamic pressure uncertainties. In this context, the proposed method is applied to some sample mission scenarios as, for example, the minimum-time transfer towards some near-Earth asteroids.



Hourly variation of the solar wind dynamic pressure at a Sun distance of 1 au.

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E-sail Attitude Control with Tether Voltage Modulation

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Conference Topic: Electric Sails for Interplanetary Exploration and Science

An Electric Solar Wind Sail (E-sail) is a propellantless propulsion system that gains thrust from the interaction of solar wind particles with a grid of long charged tethers. The tethers are deployed and maintained ideally stretched by spinning the spacecraft about a symmetry axis. The actual sail shape is not simple to calculate, as it results from the complex interaction between the solar wind pressure and the centrifugal force due to the spacecraft rotation. This problem has been addressed in recent papers [1, 2], which deal with closed-form expressions of thrust and torque vectors of a spinning and axially-symmetric E-sail. In particular, the results discussed in Ref. [1], based on the assumption of a Sun-facing sail, show that the equilibrium shape of each tether can be approximated by a natural logarithmic arc when the spacecraft spin rate is sufficiently high. On the other hand, Ref. [2] deals with the problem that the E-sail may also generate a transverse thrust, under the assumption that it maintains a rigid shape. In that case, the propulsive torque induces a perturbation on the orientation of the spin axis, which experiences an undamped precession-nutation motion. Because the external torque causes the long-period thrust to be oriented along the Sun-spacecraft direction, this perturbative effect should be removed. To this end, Ref. [3] proposes the use of a simple control law, which counteracts the generation of the external torque by suitably adjusting the tether electric voltage without modifying the total thrust. An interesting result of Ref. [3] is that just a small change in the tether electric voltage is sufficient to reduce the effects of the external torque.

The aim of this paper is to extend the previous work, by describing a new strategy for generating a desired torque necessary to change the spacecraft attitude, starting from a Sun-facing condition. To that end, the E-sail is ideally divided into four subsets, each one being characterized by a different value of the electric voltage. The time evolution of the required torque and of the necessary tether voltage is obtained by enforcing the desired time variation of the sail pitch angle, in the form of a third order polynomial. With such a control law, it is shown that the maximum required torque is proportional to the initial spacecraft angular momentum and to the desired change of pitch angle, while it is inversely proportional to the attitude maneuver time. It is shown that the required torque may be generated with a small change of the electric voltage with respect to its nominal value.

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Electric Sail Phasing Maneuvers for Constellation Deployment

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Conference Topic: Electric Sails for Interplanetary Exploration and Science

An Electric Solar Wind Sail (or E-sail) is a promising and propellantless propulsion system concept, which is capable of generating a propulsive acceleration by exploiting the electrostatic interaction among a grid of tethers (kept at a high positive potential) and the charged particles immersed in the solar wind plasma. The peculiarity of an E-sail may be exploited for envisaging new heliocentric mission scenarios, such as the maintenance of non-Keplerian orbits, or Solar System escape trajectories.
In particular, this work analyzes a heliocentric phasing maneuver by means of an E-sail, which could be used to deploy a constellation of spacecraft for scientific solar observation purposes. When a spacecraft performs a phasing maneuver, it starts from a given heliocentric working orbit, and returns on the same initial orbit, but with an angular displacement relative to the position that it would have occupied in case of a Keplerian motion. The work is conducted by using the recently proposed thrust model for an E-sail [1], which provides an analytical expression of the propulsive acceleration vector as a function of the heliocentric distance and the sail attitude.

The analysis of a phasing maneuver may be usually addressed with two different strategies. The first one involves the Hill-Clohessy-Wiltshire equations [2], which are valid as long as the distance between the instantaneous position of the spacecraft and that of the reference (working) orbit is sufficiently small. The integration of these equations provides a set of analytical expressions that give the spacecraft position as a function of time, so that the required maneuver time and the angular displacement can be calculated when the E-sail (fixed) attitude has been selected. A maneuver performed with such a strategy would guarantee a very simple mission design in terms of control law. However, the phasing maneuver can be analyzed even within an optimal framework, where the optimal trajectory for a propellantless propulsion system coincides with its minimum-time trajectory. The aim of this work is therefore to find the optimal control law of the E-sail attitude and the corresponding minimum maneuver time by means of an indirect approach. The performance of the system in some representative mission cases are also discussed.

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Distributed Attitude Control of Solar Wind Electric Sail

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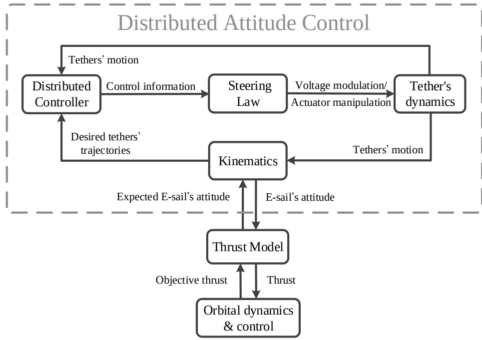
Conference Topic: Electric Sails for Interplanetary Exploration and Science

Due to a high propulsive efficiency and a low thrust-decay pattern within the solar system, the solar wind electric sail (E-sail) is rather competitive in interplanetary exploration.

A typical E-sail consists of a cluster of charged tethers which spin around a vertical axis and are centrifugally stretched with remote units fixed in the tips. To provide a required thrust, the E-sail should have a steady shape and an appropriate attitude which essentially depend on the tethers' motion. Since the motion of each tether is influenced by both the distributed forces caused by deflecting positively charged solar wind particles and the control forces exerted by the auxiliary actuators at the tether tips, it is predictable that the sail shape and attitude could be controlled by modulating the voltage and manipulating the auxiliary actuators of each tether.

Following this idea, the distributed attitude control of E-sail is investigated in this work. The desired trajectories of each tether are obtained from an expected E-sail attitude manoeuvre composed of the changes in sail shape, orientation or spin rate. The E-sail's attitude dynamics model is established by taking the tethers' angular velocities as the generalized speeds and with the coupling of tethers' motion into consideration. Then, to drive each tether tracking the corresponding trajectory separately, a distributed control method is employed. The steering laws for main tethers' potential and multiple actuators included in the remote units are also developed. Finally, numerical examples are shown to validate the given control method and steering laws.



Distributed Attitude Control for E-sail

Three Years of Deep-Space Electrostatic Propellantless Propulsion (D-SEPP) of E-Sail Investigations Performed at NASA-MSFC

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Conference Topic: Electric Sails for Interplanetary Exploration and Science

The Deep-Space Electrostatic Propellantless Propulsion (D-SEPP) or Electrostatic Sail (E-Sail) is a new propulsion technology that uses the solar wind to produce thrust without the use of propellant, enabling low-cost, rapid trip times (~10 years) to the edge of the solar system previously considered impossible. The E-Sail uses the momentum of solar wind ions for spacecraft propulsion with the help of long, positively charged wire(s). The system produces a thrust vector radially outward from the Sun, but which can be turned at will up to 30° angle and whose magnitude can be easily adjusted.

The E-Sail design is a novel approach to solar propulsion. The derived thrust predictions that such a system will generate at 1 AU were found to be ten times greater than the earlier estimates made by the E-Sail inventor. Our derived thrust estimates are based upon extensive plasma chamber testing at the MSFC. The thrust that is produced by a D-SEEP system declines at a rate of ~1/r (where r is the solar distance) and can provide useful thrust out to distances of 15 to 20 Astronomical Units (AU). Unlike other propellantless concepts such as solar photon sails, the electric sail does not rely on a fixed area to produce thrust. In fact, as the electric sail moves away from the sun, the electrostatic repulsive sheath dynamically changes, allowing the positive electric field to grow, increasing the apparent area of the virtual sail as the solar wind plasma density decreases.

Studies performed at the NASA George C. Marshall Space Flight Center show that a D-SEPP propelled spacecraft can travel to the Heliopause in less than 10 years, a feat Voyager 2 took 35 years to accomplish. Additionally, out of plane Solar Polar Orbiter spacecraft missions are also enabled by this revolutionary propulsion system as this system may enable a fifteen degree plane shift per year. E-Sail propulsion exceeds the 2012 Heliophysics Decadal Survey speed goal of 3.8 AU per year. Put in more human terms, the E-Sail technology will bring the time frame of Heliopause (and beyond) missions to well within a person's career. Most of the subsystem technologies required to field an Electric Sail are at Technology Readiness Levels (TRL) greater than 4, with several having been previously space-qualified.

ESTCube-2 Team

Thin multi-wire Coulomb drag tether by diffusion bonding

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Conference Topic: Electric Sails for Interplanetary Exploration and Science

The electric solar wind sail (E-sail) is a propulsion technique, which uses long, thin electrically charged tethers to harness the momentum of solar wind in order to generate thrust. [1] The plasma brake is a spinoff of E-sail. It uses the same physical phenomenon, Coulomb drag, in the ionospheric plasma to de-orbit satellites from low Earth orbits. First Coulomb drag payloads have flown on-board nanosatellites ESTCube-1 and Aalto-1 using ultrasonically bonded tether. [2]

A more robust E-sail tether production process is being developed by the authors. The tether is a fabric of multiple filaments, making it resistant against cuts by micro-meteoroids. Such structure is achieved by bonding several wires together. Our method is based on diffusion bonding of metal wires with diameters ranging between 20 and 50 µm. Figure 1 shows a closeup of the bonding apparatus. Two parallel wires can be seen crossing over two bonding plates at the centre of the picture.

Our next goal is a) to produce a space mission qualified Coulomb drag tether of 300 metres in length and b) to develop a test facility for our tethers. The most important tests include verification of reliable reel-out with pull forces reaching below 1 mN and pull strength tests of individual bonds. A specific apparatus is being developed for destructive testing of pull strength.

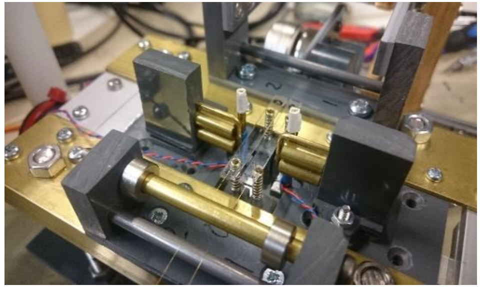

Figure 1. Closeup of bonding apparatus.

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Deployment dynamics of spinning Electric Solar Wind Sail with variable length tethers

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Conference Topic: Electric Sails for Interplanetary Exploration and Science

This paper studies the deployment dynamics of a spinning Electric Solar Wind Sail (E-sail) system. In current work, only the radial deployment mechanism is considered, and each tether has its own spool. To describe the deployment of tether, the variable-length cable element is developed based on the nodal position finite element method in the Arbitrary Lagrangian-Eulerian framework. To achieve the length variation of tether, the manipulation of merging and dividing of elements are conducted to avoid the element too long or too short. In current work, the main satellite is finite size rigid body, the dynamic coupling between main satellite and tethers are investigated. The flexural deformation of tether under different spin rates of mother satellite is investigated, meanwhile the stability problem after the tethers are fully deployed is analyzed. The deployment speed impact on the dynamic behaviour of E-sail when the spin rate of main satellite is kept constant. Finally, the dynamic behaviour of E-sail when one or several tethers gut stuck is investigated.

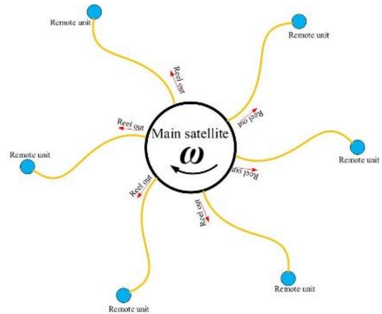

Figure 1 Schematic of E-sail system with radial deploying strategy

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Elastodynamic Modelling of Partial Space Elevator with Multiple Climbers

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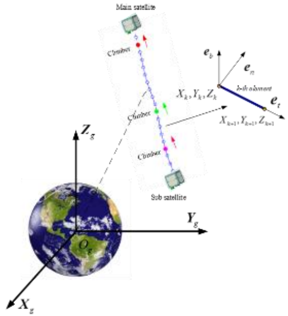
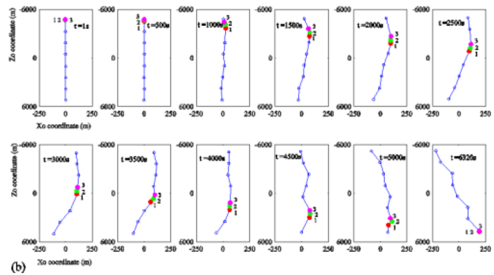
Conference Topic: Space Tether Modeling Techniques

This paper presents a novel modeling method for the partial space elevator system. To accomplish the climbers moving along the tether, the material coordinate is introduced as the state variable. The partial space elevator system is built up by the nodal position finite element method in the framework of arbitrary Lagrangian-Euler description. In the arbitrary Lagrangian-Euler description, the position coordinate and material coordinate is decoupled, and the element nodes have variable material coordinates that allowing the finite element to change its position within flexible body. The nodes where the climber locates are defined as a moving node, and the elements connecting with the moving nodes are defined as the variable-length elements. The movement of the climbers is accomplished by changing the length of variable-length element with the dividing/emerging of element process. The accuracy of the proposed method was validated by a partial space elevator with one climber in two different scenarios. Furthermore, the numerical simulation for a partial space elevator with multiple climbers is conducted in a prescribed motion. The simulation results show that the proposed method can be easily extended to multiple-climber case by assigning the moving nodes and variable-length elements.





Numerical Analysis of Tape-Like Low Work Function Tether Interaction With Ionospheric Plasmas

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Conference Topic: Space Tether Modeling Techniques

Low Work-function Tethers (LWT) [1,2] are a promising technology for propellantless space propulsion. The modelling of the charge exchange between the LWT and the ambient plasma, i.e. electron collection/ emission, is a critical task, because the performances are strictly related to the electric current. For cylindrical tether, a self-consistent kinetic model for the thermionic and photoelectric electron emission has been developed [3].

This work presents numerical results for the characteristic curves (current density versus tether-to-plasma bias, J-V) of a LWT with a tape cross-section, which is advantageous from a performance point of view. A new kinetic code has been developed by following a similar algorithm to the one used for bare tethers without emission [4]. It is a parallelized 2-dimensional stationary Vlasov-Poisson solver that uses a non-structured triangular mesh. After validating the code with previous results on cylindrical tethers, the code has been used to find the J-V curves and the plasma distribution functions around tape-like LWTs. Parametric analysis varying the ion-to-electron temperature and the tape width-to-Debye length ratios are presented.

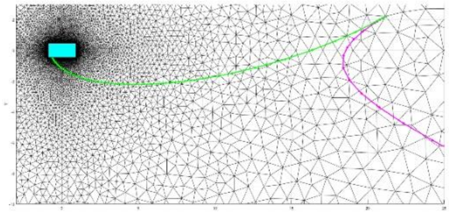

Figure 1. Electron (magenta) and ion (green trajectories)

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A simulation of the TSS dynamics in the case of the tether winding on the end bodies

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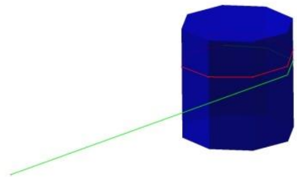
Conference Topic: Space Tether Modelling Techniques

From everyday experience we know that if a tether is a attached to the body, then under the certain conditions the tether can be wrapped around this body. Nevertheless, it looks so that the influence of the tether winding and unwinding events on the motion of the TSS has not been studied. The reason is probably that the specialists in the TSS dynamics consider tether winding as an emergence event usually: it should be avoided and if it happens, then the chances for further normal functioning of the system are low.



The tether winding on the end body

Another paradigm appeared recently in the studies on robotics: it is proposed to use tether winding for the motion control [1,2]. As a tool to study similar control strategies for space tethers we developed simple simulator of the TSS dynamics that takes into account both the tether winding on the end bodies and the unwinding.

In our simulator end bodies are assumed to be convex polyhedra. Neglecting the mass of the mass of the tether, we concentrate our attention on the variation of the tether's tension as a result of the contact with the next face of the polyhedron in the process of the winding or due to the separation of the tether from certain face when unwinding. It is supposed that if the tether segment comes in touch with the polyhedron's surface, it clings to it, while retaining the same extent of stretching. The inertia forces arising as a result of the polyhedron's rotational-translational motion do not lead to the tether break-off. Nonetheless, the tether can detach from the surface if either end of the Tether segment clinging to a face becomes exposed to the "unwound" segment tension that has a positive projection onto the normal line to this face. We present several examples of the TSS motion, obtained using our simulator.

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Detection and Orbit Determination of Tethered Satellite Systems

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Conference Topic: Space Tether Modeling Techniques

Current dynamical models used for Initial Orbit Determination (IOD) and Orbit Determination (OD) are not suitable for tethered satellite systems (TSS) because they do not account for the presence of a tension force in the dynamical model. This may lead to an erroneous determination of the orbital parameters of the system. Therefore, it can potentially represent an issue for tracking from ground present and future TSS. The proliferation of national and private space surveillance and tracking (SST) systems and the launch of new TSS missions have renewed the interest on the problem of TSS detection. Several previous works have dealt with the problem of TSS identification and orbit determination. A seminal work [1] proposed a way of identifying TSS and discriminating them from ballistic missiles, using actual tracking measurements. In 2001, Cho et al. [2] revisited the problem, using rigid body dynamics to model the TSS and including their out-of-plane motion. Both works have used batch processing for the statistical treatment of the surveillance data. Later works have explored the utilization of alternative techniques to tackle ill-conditioned scenarios [3] or sequential filtering in the orbit and attitude determination of TSS [4,5].

The contribution of this work is the development of a method to detect non-cooperative TSS with minimum modifications of current OD techniques. The method is based on Dumbbell model dynamics. The state and variational equations required in the propagation step of the orbit determination process are derived. The solution approach presents two steps. In the first step, slight modification of current orbit determination algorithms allow us to identify TTSs. In a second step, the orbit determination of a TTS is performed. Validation of the approach is done using synthetic measurements from high-fidelity simulation. In addition, the solution approach is to be implemented within the frame of ODTBX toolbox [6].

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An object-oriented multidisciplinary framework for Space Tethers simulation

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Conference Topic: Space Tethers modelling techniques

Space tethered systems have been proposed for a number of different innovative mission concepts: generation of artificial gravity, formation flying, propulsion, etc. Tethers are considered as parts of more complex devices as harpoons or hooks. In the context of space debris mitigation and removal, an additional rationale for the advance in the accurate simulation of tether dynamics is the promising capabilities of electrodynamic tethers to de-orbit a satellite efficiently.

The dynamics of tethered spacecraft involves nonlinear effects with dynamical coupling among orbital motion, longitudinal, and lateral modes. Although different approaches have been considered in the literature to address the simulation of space tethers, there is still a need to: 1) simulate the dynamical behaviour with required accuracy and acceptable time consumption, 2) suitable characterization of tether flexibility in different complex tethered configurations and 3) simulate the tether within the same framework as other spacecraft subsystems.

The work presented here is intended to fulfil this need using a new tether dynamical model and a non-casual and object-oriented modelling approach, providing the space community with a flexible and robust simulation environment for many of the aforementioned possible applications of space tethers. The focus in this work, nonetheless, is the simulation of tethered satellites and electrodynamic tethers in particular.

The space tether system is described in terms of a number of elastic rods, joined by ideal joints. The end masses can be modelled as point masses or rigid bodies. The proposed formulation allows modelling several tethers joined to a same spacecraft. In turn, the flexibility of the non-casual modelling technique allows us to obtain robust mathematical models for complex physical systems.

A simulation toolkit for the simulation of space dynamics and space tether systems has been developed for the multidisciplinary simulation tool EcosimPro. The core of the library is the orbit propagator of the masses, based on DROMO method, although Cowell’s method can also be used. Common space dynamics capabilities are also included, as spacecraft attitude dynamics and trajectory calculation in different space environments. In this way, it is possible to simulate the whole tethered satellite system within a single simulation framework, including other spacecraft coupled systems as the attitude and orbit control system or the power system.

A validation is performed using examples from the literature and experimental results when available. Then, test cases are used to evaluate the performance of the library in terms of computation time. Finally, a full de-orbiting mission of an electrodynamic tethered system is presented.

Reduced-order Modeling of Tethered Systems using Mem-Models

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Conference Topic: Space Tether Modeling Techniques

The topic described in this paper launches a new theoretical framework involving a multidisciplinary study to efficiently capture the memory effect (path-dependency) in with highly nonlinear materials, complex media, and strongly coupled dynamical systems, using tethered systems as a mechanical prototype. In particular, this work leverages the recent work on Smart Tethered Systems ([1],[2],[3]). The theoretical foundation is based on developing an integrated viewpoint for the em-models based on the multi- physics bond graph theory and the memristor/memristive system theory dealing with memory effect in nonlinear circuit theory. The proof-of-concept of past relevant work in this area was the result of recent work to transfer the mem-models to the engineering mechanics domain ([4],[5]). There is a wide range of systems that this long-range effort will impact: intelligent material phase transition (ferroic materials, SMA, piezoelectrics for actuators); soft matter response (programmable materials); composite materials on stitutive relations involving geometry nonlinearity and discontinuous stress-strain response, as needed to design more efficient material solutions for autonomous systems involving tethers. Nonlinearities and hysteresis are inherent to phase transition thereby call for adequate and efficient modeling formulation for phase transition-based tethered system, e.g., for small body sample capture. We put forth a new modeling framework, memcapacitor and memcapactive system model that are originated from electrical engineering and multi-domain physics. This theoretical framework first leads to a fundamentally nonlinear model family that is built on differential algebraic equation (DAEs) with instantaneous switching behavior, suitable for capturing phase transition. This theoretical framework also directly utilizes absement, time integral of displacement, a new state variable serving as a direct and powerful means of realizing the memory effect, i.e., hysteresis in the system due to path-dependency.

Acknowledgments: U.S. Government sponsorship acknowledged. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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Tether System Design for the Bi-Sat Observations of the Lunar Atmosphere above Swirls (BOLAS) Mission

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Conference Topic: Space Tethers for Space Environments Research

The Bi-Sat Observations of the Lunar Atmosphere above Swirls (BOLAS) mission concept will use a pair of tethered satellites to determine the role of the solar wind in weathering and water production on the surface of the Moon. The BOLAS mission, developed by a NASA/Academia/Industry team led by NASA Goddard Space Flight Center, will use a 25-km long tether to enable two small satellites to fly in formation in a 'frozen' lunar orbit while allowing the lower satellite to dip down to altitudes of just a few kilometres above the lunar surface.

In this paper, we will present results of trade studies and design exercises to develop a design for the tether and tether deployment system for the BOLAS mission. The tether system design had to meet tight volume and mass restrictions while providing reliable, controllable deployment of the tether and ensuring survival of the tether in the near-surface lunar environment for a duration of 6 to 12 months.

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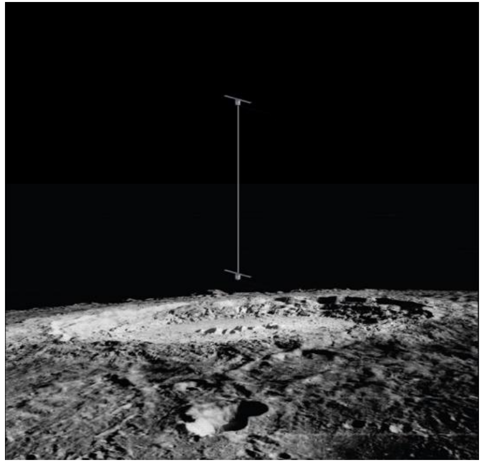

Fig. 1. The BOLAS Mission will use tethered formation flight to enable long-duration measurements of the environment within a few kilometres of the lunar surface.

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Ways to Moon's low orbits for cubesat science: comparison between the use of passive tethers and "shape based" trajectories with low thrust electric propulsion

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Conference Topic: Space Tethers for Space Environments Research

Recent advancements in micro satellite technology are paving a new era for space missions extending the potential of small satellite mission to a wide range of applications for space and planetary exploration. The result is a fast-growing interest in their use in dedicated scientific mission as demonstrated by the latest involvements of main space agencies in the definition of missions envisioning application of cubesats for Moon exploration. The intrinsic characteristic of the Moon environment requires low altitude orbiting spacecrafts for mapping key parameters such as plasma, volatiles and magnetic field.

Inserting a small satellite in such low trajectories from an orbiter has usually a high cost of propellant with classic transfer methods (not compatible with cubesat mass) or requires a long time to finalize the maneuverer with electrical propulsive systems. The use of a long passive tether to exchange momentum between two cubesats can eliminate such drawbacks and provide fast, far-reaching and accurate orbital changes with almost no propellant being consumed. On the other side by properly defining a thrust profile for the electric motor using "Shape Based" trajectories a predefined orbital track can be obtained, allowing multiple observation of particular features on the surface.

A comparison of two mission scenarios to reach a low Moon orbit is presented using a mission baseline with an orbiter in circular Moon orbit at 500 km altitude: the first one foresees a single cubesat with low thrust propeller, the other a dual cubesat system with a deployable 60 km passive tether. Advantages and drawbacks of the two solutions in terms of time of flight, mass of equipment, fuel consumption and operation in low orbit are analysed by numerical simulation and parametric analysis.

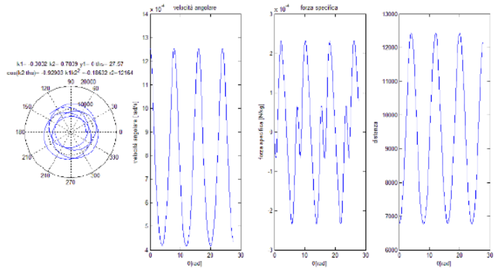

Fig. 1. Example of a "shape based" trajectory elaboration

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Electric Power Module for a Bare Electrodinamic Tether

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Conference Topic: Tether Power Generation and Energy Harvesting.

One of the key aspects of the functioning of an electrodynamic tether is the handling of the power being delivered to the satellite while in operation and the powering of the hollow cathode subsystem that balances charges within the satellite. The present paper addresses the identification of the main specifications and design of the tether power system for a telecommunications satellite for the purpose of its de-orbit at the end of life [1].

The power supply under design has two main objectives: provide power to the Hollow Cathode system and dissipate (or possibly regenerate) the electrical energy injected by the electrodynamic tether. The block diagram of the complete power supply is presented in the Figure.

The power supply is directly connected to the satellite power bus, through an EMI filter and mandatory protection elements, and to the onboard computer, for telemetry status and possible control of the tether system. An autonomous system could be obtained by optionally including a battery, and a battery charger, which will be maintained fully loaded by the satellite power bus until the tether is operated at satellite End-O_-Life. At that moment the battery will supply initial power for the Hollow Cathode start-up and the system will switch to the electro-dynamic tether regenerative load for subsequent power production. The Hollow Cathode needs three power supplies for the operation: two low voltages for its electric valve drivers and the heater and a high voltage for the anode [2].

A telemetry and control unit completes the set and provides telemetry and operation of the whole system, including autonomous operation if the system is programed to operate autonomously, and the control of libration of the electro-dynamical tether.

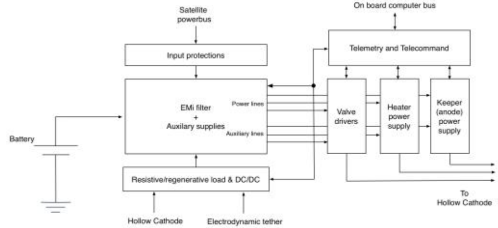

Fig. 1. A general view of the considered power system.

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CubeSat Payload to Demonstrate Electrodynamic-Tether Energy Harvesting

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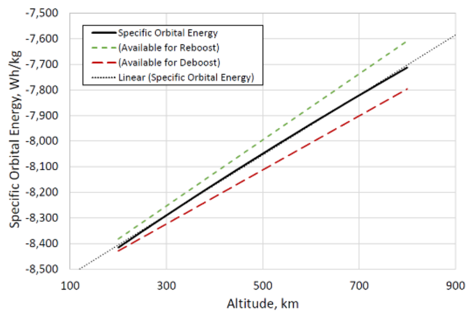
Conference Topic: Tether Power Generation and Energy Harvesting

McTernan and Bilén [1] showed that a significant amount of the embodied energy in "space junk" could be "repurposed" for use onboard spacecraft via electrodynamic-tethers (EDTs). Additionally, energy harvesting on spacecraft using EDTs [2,3] has been proposed to augment or enable mission capabilities on CubeSats not currently possible due to limitations in maximum power capability. Finally, energy from the "orbital battery" (Figure) can be harvested and stored for use later in propulsive maneuvers.

We present a concept for a CubeSat-scale payload to demonstrate EDT energy harvesting. Although power generation has occurred on flown EDT systems, this power has not been stored for later use nor for immediate use in spacecraft systems external to the EDT system itself. The proposed Energy Harvesting Demonstration Module (EHDM) will demonstrate the ability of an EDT satellite system to harvest, store, and then use that energy. The design of the system is presented, as well as mission orbital profiles determined via the use of TeMPEST (Tethered Mission Planning and Evaluation Software Tool).



The capacity of the "orbital battery" is ~1.08 Wh/(km·kg) [1].

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SmallSat Tethered Constellations for Seismic Monitoring

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Conference Topic: Novel Science Measurement Using Tether Technology

This paper takes a look at what innovative science measurements can be achieved by SmallSats and CubeSats connected by tethers. Here, we assume that CubeSats are in the range of 4 to 25 kg (3U to 12U), and SmallSats are in the range 25 to 100 kg. Due to the low cost of SmallSats and CubeSats, new modalities of scientific observations are possible, specifically exploiting the concepts of tethered constellation or formation, and of sensor disaggregation [1]. A few significant general characteristics emerge. For example, instrument resolution (strength, direction) is dictated by spatial sampling in the measurement, leading to novel constellation types. High sensitivity in the frequency band of interest is dictated by temporal sampling, leading to novel requirements in instrument bandwidth. Exploiting such richness in spatial and/or temporal sampling allows for observations of physical processes thus far precluded, such as highly dynamic changes needing high resolution, as in the case of seismic event detection. The ionosphere has been shown to experience disturbances prior and during seismic events, and waves of various types and frequencies (particularly a change in total electron content) are emitted from the surface during such events [2]. The tethered constellation senses the ionospheric disturbances by experiencing a distortion of the relative position of the tethered spacecraft, thus putting the network in motion. As an example, a long orbiting tethered spacecraft, for example, which naturally would be aligned with the radial direction due to its gravity-gradient equilibrium, would be forced to initiate in-orbit and out-of-orbit plane gravity gradient oscillations that could then be detected (the longer the tether, the more sensitive the detector), once an ionospheric wave impinges on the tether. At different altitudes a tether would be deformed differently as the total electron content, hence the atmospheric density, varies. Therefore, a tether could act as a low frequency acoustic gravity gradiometer to potentially detect and measure seismic events. A distributed guidance and control algorithm for the reconfiguration of the robotic swarm is introduced in [3], that allows to solve for the collision-free trajectory generation. Whentherelativeanglebetweentethersforopenandclosedconfigurationsof the constellation is compared, a much more precise system response results for in the case closed configuration, which could be further designed specifically for seismic applications.

Acknowledgments: U.S. Government sponsorship acknowledged. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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Correcting Langmuir probe measurements on small satellite structures by tracking the spacecraft potential using the twin probe technique

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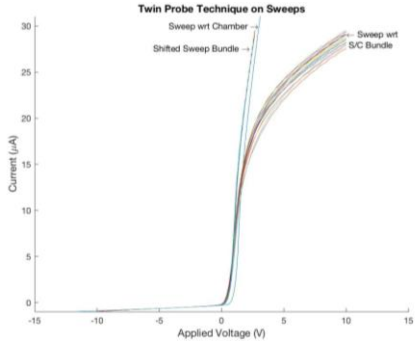
Conference Topic: Novel Science Measurement Using Tether Technology

At the University of Michigan, the Miniature Tether Electrodynamic Experiment (MiTEE-1), the first of two student-led, CubeSat missions, has been designed and built for launch in 2019. The MiTEE-1 spacecraft carries a single Langmuir probe (LP) and an end body at the end of a boom to study the current collection to a small rectangular cuboid structure in the ionosphere [1]. Due to the mission's small surface area ratio (spacecraft area to probe area), a negative charge is expected to be induced on the spacecraft during Langmuir probe sweeps. This results in a variable spacecraft potential that affects the accuracy of electron temperature and electron density measurements made by the Langmuir probe, thus, reducing its effectiveness as a diagnostic tool [2].

In support of the MiTEE-1 mission, two separate studies have been performed. Analytic expressions and a charging model, PSIC-LEO, were developed to estimate the charging levels during probe operation as a function of drift angle and CubeSat size. Additionally, a twin-probe technique for CubeSats was studied. The twin-probe technique allows the spacecraft potential to be tracked during LP sweeps by employing a separate high-impedance probe to measure spacecraft potential relative to ambient plasma potential. On a tethered spacecraft, the high impedance probe can be the tethered end-body instead of an independent Langmuir probe. Here we will present data from ground-based experiments that study the effectiveness of the twin probe technique and the challenges involved with its implementation. Additionally, we will discuss advancements in PSIC-LEO.



Chamber data of twin-probe technique using two similarly-sized cylindrical probes biased with respect to a 3U CubeSat. Sweep w.r.t. chamber continues outside of plotted area.

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Lessons Learned from SEDS, PMG, SEDS-2, and TiPS

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Conference Topic: Lessons Learned from Past Missions

This paper discusses lessons learned from the orbital flight tests of SEDS, PMG, SEDS-2, and TiPS.

I proposed SEDS in response to NASA's first SBIR solicitation in 1983. It was funded through Phase 1 and 2, and then follow-on funding. SEDS was managed by the Advanced Projects Office at NASA Marshall. Initial plans were to fly it on the shuttle, but after Challenger, NASA decided to fly it as a Delta/GPS secondary payload. It flew in March 1993. It deployed a 20 km Spectra tether with a large swing that slung its 26 kg payload into a targeted reentry near Baja. Burnup was videotaped by NASA JSC.

NASA JSC asked me to adapt SEDS to deploy an insulated 500m 18-gauge wire for its Plasma-Motor Generator test, also planned for a Delta/GPS launch. This used the SEDS/Delta interfaces to reduce costs, but with a new deployer design more suitable for a stiff wire. PMG deployed in June 1993. About 400m of the wire deployed, but little of the passive adhesive brake paid out at the end.

The success of SEDS led NASA to fund a follow-on Delta/GPS test to stabilize a SEDS tether near the vertical, rather than with a large swing. Enrico Lorenzini of SAO developed the control law. SEDS-2 deployed in March 1994, with a residual swing amplitude of 4°.

SEDS-2 got considerable public attention because the 0.8mm x 20 km tether was often visible to the naked eye.

SEDS-2 was the first man-made structure in orbit to be visible to the naked eye as a line rather than just a point of light. But 3.9 days after deployment, the tether was cut, probably by a micrometeoroid. The 7 km remaining attached to the Delta was visible under good viewing conditions for most of its remaining 2 month orbit life. Based on video and drag trend data the 7 km length appeared not to have been cut again. This suggests that the first cut was apparently somewhat unlucky.

Based partly on the SEDS-2 tether cut, the Naval Research Laboratory proposed in late 1994 a "Tether Physics and Survivability" test ("TiPS") of a thicker 4 km tether using the SEDS deployer. To reduce vulnerability, I suggested using a springy acrylic yarn inside a heavier Spectra braid. This increased the deployed tether diameter to >2mm, and also reduced its density. That probably reduced the damage cone angle from impacts. TiPS was deployed in June 1996 at 1022 km altitude. It remained intact for 10.07 years, longer than most analysts expected.

The above tests led to proposals of more ambitious tether concepts by ESA, NASA, and other organizations. They led to TAI developing and testing new flight hardware, but as is often the case in the space business, none of those projects led to actual flight tests. The paper briefly summarizes lessons from those 7 projects: YES, Mir reboost, ProSEDS, TREV, ION, CE2, and EDDE.

Development of a Magnetized ExB Plasma Device

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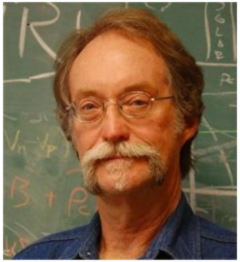

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Conference Topic: Lessons Learned from Past Missions

Propulsive Tethered Satellite Systems, PTSS, depend on exchanging current with ambient plasma and thus momentum with the Earth's magnetic field. The Air Force Research Lab, AFRL, is pursuing an investigation of momentum coupling in plasmas for a number of applications including the PTSS. Other interests include, magnetosphere-ionosphere coupling, solar eruptions, and the Critical Ionization Velocity (CIV) mechanism. The Space Shuttle Tethered Satellite experiment, TSS-1R, [Thompson, GRL,1998] demonstrated a surprising lack of theoretical and experimental understanding of the general problem of a positive probe in a flowing plasma. Since that time, there has been significant activity across the community in addressing these needs in engineering and science, but one capability still needed is an approach to a plasma chamber capable of establishing a true ExB drifting plasma.

Addressing this need, AFRL has been construction such a device, EMPD (ExB Magnetized Plasma Device) using a 1m diameter by 2 m long cylindrical chamber with field coils capable of 300 Gauss. Scaled experiments will allow the study of current wings, electrodynamic phenomenon, and of course useful current-voltage measurements. In addition to presenting progress and results from EMPD, other AFRL activities related to PTSS will be reviewed.

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Performance of EDT System for Deorbit Devices Using New Materials

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Conference Topic: New Materials for Tether Applications

A large number of microsatellite missions are currently being planned or prepared. Deorbit device is required to meet space debris mitigation guidelines, but it is severely challenging in terms of resource limitations. The authors are conducting research on deorbit devices using electro-dynamic tether. A deorbit device with electrodynamic tethers is expected to have high deorbiting performance even in high orbit by using both the Lorentz force and atmospheric drag. In the previous study, aluminum and polyester were used as materials of the tether, and it had a sandwich structure in a flat tape form. This tether is called "ALPET". It has sufficient conductivity and strength by using polyester as the strength material and aluminum as the conductive material respectively. However, the weight of the tether is heavy.
Therefore, in this research, we focused on new materials such as carbon nanotube yarns and investigated the mechanical properties and electrical characteristics of the tethers knitted with the fibers in a ribbon form. In addition, the influence of parameters such as the number of fibers constituting the ribbon on conductivity and weight were examined.

Carbon nanotube yarn is taken as a representative example. It has sufficient strength, but, the electric resistivity is about two orders of magnitude larger than that of aluminum, and available Lorentz force becomes small. On the other hand, since carbon nanotube yarn are lighter than ALPET, they can be made into a wider tether with the same weight, and a large atmospheric resistance can be obtained. It is also possible to increase the conductivity by metal plating on the surface of the carbon nanotube fiber [1], but it becomes heavier accordingly. Other metal plating fiber materials are also investigated to realize high conductivity and strength simultaneously.

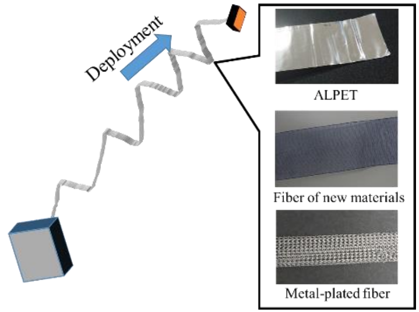

Image of “ALPET” and tether made of new materials

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Work function tuning of graphene oxide by using cesium oxide nanoparticles applied to low work function tethers

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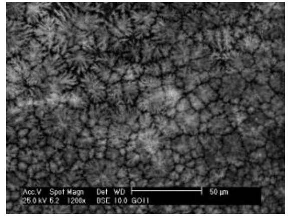
Conference Topic: New Materials for Tether Applications

Low work-function materials to enhance the electron emission through thermionic and photoelectric effects have several terrestrial and space applications, including electronic and energy conversion devices, and technologies to enable space tether missions as electron emitters, among others. This work is focussed on a recent concept named low work-function tether (LWT), which is a km-long tape orbiting in space and made of a conductive substrate coated with a low work-function material [1, 2]. The operation of the LWT in de-orbiting scenarios is fully passive and free of consumables.

The study presents a synthesis process of cesium oxide (CsO) nanoparticles and graphene oxide/cesium oxide (GO/CsO) nanocomposite by using a simple hydrothermal method [3]. GO and synthesized GO/CsO nanocomposite were deposited on an Aluminum (Al) 2cm x 2cm x 50microns tape by using spray coating method and later were reduced by thermal annealing. The different coatings/materials prepared were characterized by means of XRD and FEG-SEM techniques. The electron thermionic emissions capabilities from the reduced GO coating and GO/CsO nanocomposite coating (ignoring the effects of the substrate) were investigated by heating the samples and measuring their voltage-current characteristics in vacuum chamber experiments. The work function of GO, GO/CsO, and CsO nanomaterials were obtained from the thermionic emission data. The results showed that, by intercalating the CsO nanoparticles into the GO matrix, the work function of the GO decreased drastically and led to increasing thermionic emission from the GO coating on the Al tape. The suitability of the coated tapes to low work-function tether applications is discussed.



LWT SAMPLE

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Trade-off Analysis of C12A7:e- Deposition Techniques Applied to Low Work Function Tethers

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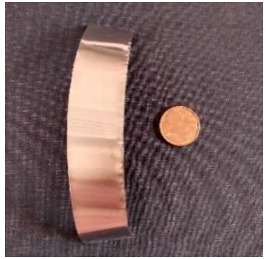
Conference Topic: New Materials for Tether Applications

The C12A7:e- electride [1,2] is one of the most promising materials for Low Work Function Tether (LWT) applications [3,4]. The material comprises a set of extraordinary properties that include a high electronic conductivity, extremely low work function, and stability. However, the coating of a km-long conductive substrate (Aluminium tape) with a thin layer of C12A7:e- to enhance the passive thermionic and photoelectric electron emissions of the tether under the illumination of the Sun is still an open problem. LWTs should meet a precise set of mechanical and optical requirements.

This work presents experimental results of C12A7:e- deposition techniques on conductive substrates by using three different techniques: magnetron sputtering, Pulsed Laser Deposition (PLD) and Physical Vapor Deposition (PVD). The implemented manufacturing processes and the corresponding diagnostic techniques for each deposition method are described. There are critical post deposition treatments that are necessary to repair the surface structure and recover the emission properties. Trade-off analyses are presented in terms of critical feature for tether applications such as work function, uniformity of the coating, and feasibility of the technique for coating km-length aluminium tapes.

The thermionic emission capabilities of the samples were studied by measuring thermionic currents in vacuum facilities. By biasing the emitter relative to an electron-collecting anode, the current-versus-bias (I-V) characteristics were measured at different sample temperatures and effective work function and material-correction factor for Richardson constant were inferred.



LWT sample by ATD

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TiS 2019 Notes

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- 1st International Conference on Tethers in Space
  17-19 September 1986
  Virginia, USA
- 2nd International Conference on Tethers in Space
  4-8 October 1987
  Venice, Italy
- 3rd International Conference on Tethers in Space
  17-19 May 1989
  San Francisco, CA, USA
- 4th International Conference on Tethers in Space
  10-14 April 1995
  Smithsonian Institution, Washington, DC, USA
- 5th International Conference on Tethers in Space
  24-26 May 2016
  University of Michigan, Michigan, USA
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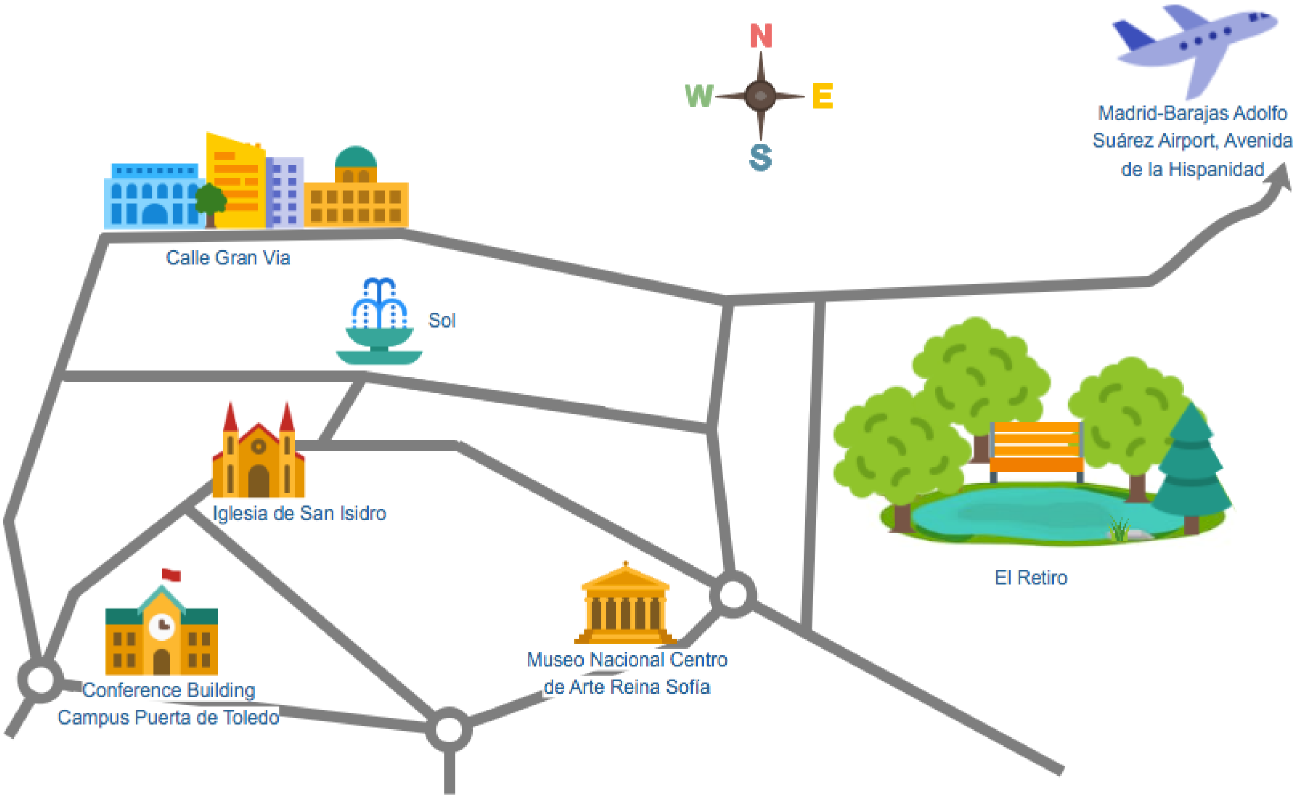

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