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Fixed-axis electric sail deployment dynamics analysis using hub-mounted momentum control

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A B S T R A C T

The deployment dynamics of a spin stabilized electric sail (E-sail) with a hub-mounted control actuator are investigated. Both radial and tangential deployment mechanisms are considered to take the electric sail from a post-launch stowed configuration to a fully deployed configuration. The tangential configuration assumes the multi-kilometer tethers are wound up on the exterior of the spacecraft hub, similar to yo-yo despinner configurations. The deployment speed is controlled through the hub rate. The radial deployment configuration assumes each tether is on its own spool. Here both the hub and spool rate are control variables. The sensitivity of the deployment behavior to E-sail length, maximum rate and tension parameters is investigated. A constant hub rate deployment is compared to a time varying hub rate that maintains a constant tether tension condition. The deployment time can be reduced by a factor of 2 or more by using a tension controlled deployment configuration.

1. Introduction

The E-sail is a novel propellantless in-space propulsion concept with great potential for fast interplanetary and near interstellar missions, invented and proposed by Pekka Janhunen [1] at the Finnish Meteorological Institute. In this concept, a system of radially configured, thin, charged tethers generate an electric field that interacts with solar wind protons to harvest acceleration for spacecraft propulsion, demonstrated in Fig. 1. This provides infinite specific impulse and eliminates the need for traditional chemical propellants [2]. Only an electron gun is required to maintain a positive electrostatic charge on the tethers. The positive solar wind ions deflect of the results E-sail tether force field, causing a net force onto the spacecraft. This solar wind propulsion concept is advantageous in comparison to the solar radiation pressure (SRP) based solar sail due to the effective area of the electrostatic forces and improved solar radius dependence [3]. A single charged wire, microns thick, will create a meters-wide effective area, expanding the area of influence of a minimal structure. In comparison, SRP is directly dependent on the physical area of the solar sail, providing many challenges in manufacturing, packaging, and deploying large membranes [4]. The solar radius dependence of the E-sail has been shown to decay the acceleration at $1/r^{7/6}$, slower than that of the solar sail at $1/r^2$. This is encouraging for long distance missions to the outer planets and beyond. However, the E-sail is not operable within a planet's magnetosphere, where the solar wind protons are deflected, whereas a solar sail still accelerates on the photons in this region.

Multiple missions have been designed using the E-sail as the primary propulsion system with encouraging results. A fast entry probe mission to Uranus could be achieved in less than 6 years [5], the interstellar medium reached in as little as 10 years, and a near Earth asteroid rendezvous could be completed within a year [6]. Additionally, missions to the inner planets, such as Venus and Mars, could also be achieved in less than 1 and 2 years, respectively [7]. This provides adequate motivation to pursue further development of the E-sail system. The electrostatic propulsion theory enabling these missions has been studied in detail [3,8]. Additionally, work has been done concerning the sail shape under thrust [9] and for solving secular drift in the operating sail spin rate using only voltage modulation [10]. However, the coupled deployment dynamics of the spacecraft and charged tether system is not well understood. Typically, the E-sail systems considered are composed of 20–100 tethers, up to 20 km in length, with payload masses of 100–2000 kg. These tethers are constructed using multiple micron-thick conductive tethers with auxiliary loops, known as a Hoytether [11], to provide redundancy and protect against micrometers. Construction of such tethers at the desired length has been investigated with encouraging results [12]. One such tether, 10 m in length, was flown on the EstCube-1 [13] but was not deployed [14]. Despite this, evidence supporting the feasibility of the E-sail is continuing to develop, and steps should now be taken towards

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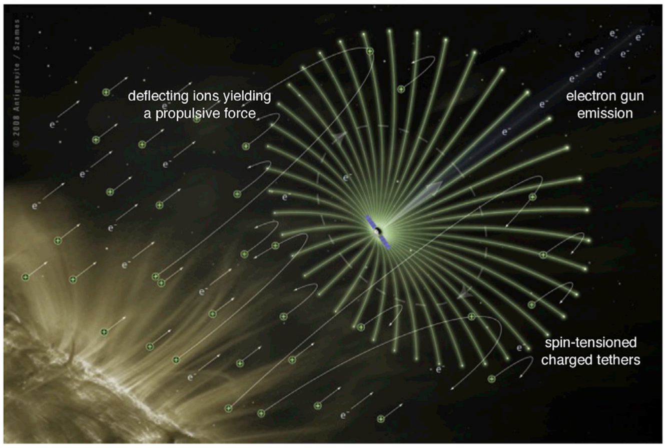

Fig. 1. The electric sail is charged by a spin axis-pointed electron beam and deflects solar wind protons to generate thrust. Artist concept image by A. Szames.

understanding the deployment requirements for such a structure.

During flight, the tethers are spin-stabilized to maintain tensioned, radial, straight line configurations. Therefore, at the end of the deployment phase, the spacecraft and each tether component must be rotating at equal rates. This can be achieved through either a centrifugal deployment or by actuating the tethers from rest using tether-mounted thrust and spinning up the tethers and spacecraft after the tethers are fully extended. In this paper, only a centrifugal deployment is considered. Due to conservation of momentum, a centrifugally deployed tether system modeled with a spherical pendulum (such as a yo-yo despinner) asymptotically approaches the negative initial rate when left in free spin. This fact can be leveraged for deployment by adjusting the tether length or initial rate such that the final desired rate is reached, however for cases where the tether length and system inertia is exceedingly large and predetermined, such as the E-sail, the initial rate required is not practical. For those cases, energy and momentum must be continually input to the system as the tethers are deploying to maintain desired body rates. The primary challenge for a centrifugal E-sail deployment is providing the momentum required to spin-stabilize the deployed structure while minimizing risk and fuel consumption, presenting a non-trivial task.

Review of the literature reveals that many tethered space system concepts have been presented and studied in the past, however none quite resemble the structure proposed here. Kilometers-long space tethers that have flown as of 2016 were single tether missions, such as in the TSS, SEDS, and TiPS missions [15]. These single tether systems used gravity gradients to actuate deployment and hosted much larger payloads, making them poor analogs for the E-sail deployment dynamics. Spin stabilized, multiple-tether systems have been proposed and studied, such as the Terrestrial Planet Finder (TPF) and Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) concepts, however the deployment requirements of these concepts are not necessarily comparable to the E-sail. The SPECS mission, for example, proposes to leverage conservation of momentum during deployment of the 3 tethers by pre-spinning the system to 90 rpm in order to approach 0.01 rpm at full deployment [16]. A quick calculation shows that a pre-spin method will not be feasible for the E-sail deployment. Where an E-sail accelerating a spacecraft at 1 mm/s^2 could easily have an inertia of 10^8 kg m^2, and the rotation rate is limited by the tension capability of the tether and end mass size, the required pre-spin rate could be on the order of 10^5 rpm. Another space structure that somewhat relates to the E-sail is that of wire booms for science payloads, as flown on THEMIS, RBSP, and MMS. However deployment here is also not directly comparable, where the wire lengths are on the order of tens of meters, and therefore do not present the same momentum challenges as the E-sail. These systems also use a spin-up strategy to take advantage of conservation of momentum during deployment [17,18], and therefore offer little additional insight for E-sail deployment solutions.

In this paper novel deployment schemes are studied where the spacecraft body rate is controlled using body-mounted devices. A body-mounted strategy will be simpler than coordinating and commanding individual tether-mounted devices to actuate deployment. Furthermore, applying torque through the hub may be possible using commercially available products, whereas tether end point thruster units are currently under development. Two deployment schemes that use a body-mounted energy source are considered. The first is a tangentially aligned deployment, where all tethers are mounted on a central hub oriented with the spacecraft spin axis, taking advantage of the rotational dynamics to deploy the tethers simultaneously. The second deployment scheme uses a radially oriented deployment configuration. Such a configuration has each tether housed on a separate spool and motor device. This paper compares the dynamic deployment behavior of these two methods. In previous work by the authors [19], the coupled rotational dynamics of the spacecraft and E-sail system was modeled during the deployment phase and initial control of these dynamics was investigated. This paper continues and expands this work through parameter sensitivity analysis and additional control schemes.

A proposed scheme for the E-sail mounts the tethers at a radial orientation [20], where each tether is housed with an individual hub and motor subsystem to conduct the tether reeling. An auxiliary tether would line the periphery of the sail, and thruster units would interface between the tether end points and auxiliary tether to control position and momentum. These components significantly increase the mass budget of the E-sail and introduce a highly complex dynamics problem. In this paper, an auxiliary tether is not included such that only a stand alone end mass is accounted for. Additionally, the deployment is assumed to occur in a single plane, reducing the problem to rotational degrees of freedoms about the deployment normal axis and ignoring out of plane dynamics. It is also assumed that the spacecraft has reached deep space conditions before initiating deployment, the sail is not charged during deployment, and the tethers do not adhere to each other as they deploy. Of interest is the nominal performance for each deployment type, as well as the sensitivity of this performance with respect to the body rate and spool reel rate. Numerical simulations demonstrate the expected performance.

2. E-sail dynamics modeling

2.1. Spacecraft and E-Sail mass model

The mass budget of the E-sail and spacecraft system is selected such that the characteristic acceleration of the E-sail at 1 Au from the Sun is between $a_\oplus = 0.1 - 1$ mm s^{-2}. At $a_\oplus = 1$ mm s^{-2}, significantly faster missions to the outer planets and beyond are feasible [5]. The characteristic acceleration is given by [20]:

$$a_\oplus = \frac{fNL}{m} \tag{1}$$

where N is the number of tethers, L is the length of the tethers, m is the total mass of the spacecraft, and f is the thrust per unit tether length at 1 AU from the Sun. Using the physical reference data for the E-sail [20], this is known to be $f = 579.84$ nN m^{-1} for an E-sail operating at 25 kV nominal tether voltage. The total system mass is set to $m = 500$ kg, a smaller but feasible mass for an interplanetary science mission, to facilitate greater focus on the other free parameters of the system. It is assumed that the maximum number of tethers is 100 and the maximum length of a tether is restricted to 20 km [20]. However, this only slightly restricts the range of E-sail sizes that will yield the desired characteristic acceleration in Eq. (1). For a scenario where there is minimal end mass, no remote devices, and minimal number of tethers with maximum length, the tethers themselves are the largest contribution to the spacecraft system momentum. Therefore, accurate modeling of the E-sail deployment requires that the tether inertia is not treated as negligible.