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"Rigid Boom Electrodynamic Tethers for Satellite De-orbiting and Propulsion"

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ABSTRACT

Due to the fact that currently most satellites don't employ any post mission disposal technique they usually end up as debris once they reach the end of their life. This only worsens the problem of the overpopulation of the near Earth space with objects, which could endanger future missions. Moreover, it is important to avoid generating new debris because once a given concentration of debris in space is reached, due to random collisions, their number could start to increase exponentially (a phenomenon known as the Kessler syndrome).

Electro-dynamic tethers (EDTs) could be used as an effective means of deorbiting spacecraft. Such systems rely on the Lorentz force generated by a long conductive tether cutting through the Earth's magnetic field due to the host spacecraft's orbital motion. Due to the generated electro-motive force a current is generated in the tether, which is sustained through the local space plasma by some form of charge exchange. EDTs have the advantage of being self-powered, and propellant-less, however, to be effective, the tethers typically have to be several km long, and be very thin to save mass. They are therefore flexible and therefore rely completely on the gravity gradient to be tensioned. This leads to such systems being most effective in low-Earth equatorial orbits, and unfortunately, much less effective in near polar orbits (e.g. Sun-synchronous orbit) where the angle between the tether and the local magnetic field is quite small. They are also prone to different forms of unstable oscillations.

A novel concept is therefore proposed by the authors for an uncontrolled removal system based on electro dynamical principles. Instead of a long flexible tether (which have proven problematic to deploy), we consider using relatively short (~150m-300m) rigid electro-dynamic booms. The main advantage of such a structure is that, for satellites in polar orbits, it leads to a larger Lorentz force. Also, the deployment is more reliable and the attitude control is greatly simplified (because the booms are rigid). A ground demonstrator is under development based around a 6U CubeSat structure.

We also analyze and evaluate different techniques which could be used for electron emission into the surrounding plasma because currently this is what limits the generated currents in the proposed system. Also we consider the performance of the proposed design when used in deep space: interplanetary missions, asteroid deflection, etc. in which case the working principle is slightly different from that used in near Earth orbits (electrostatic interactions between charged booms and the solar wind).

This work is conducted as a part of the European Commission funded Horizon-2020 TeSeR (Technology for Self-Removal) project, which aims to demonstrate the feasibility of a scalable post mission removal system which should be able to be connected to different satellites via a standard interface.

KEYWORDS: Rigid boom, electrodynamic tether, de-orbiting, propellant-less propulsion, thermionic emission.

INTRODUCTION

Propellant-less thrust of drag generation is an interesting concept for satellites which should change their orbit over long periods of time (de-orbiting, relocation) with a minimum additional mass.

One could avoid using a propellant by using large deployable structures which are able to interact with the environment: like drag augmentation sails and balloons, solar sails, electrodynamic tethers.

Electrodynamic Tethers (EDT) are long (usually a few kilometers), flexible conductive wires or tapes which can be deployed from a S/C in order to generate force. The force is due to the interaction of currents in the tether (induced by an electromotive force or by a power supply) and the geomagnetic field (Lorentz force). The current (which is almost DC) at the same time requires a certain mechanism of charge exchange at the extremities of the tether in order to satisfy the laws of electrical charge preservation. For this, usually it is suggested to use the plasma from the ionosphere. One popular concepts is that of a "bare tether" which actually consists in using a metallic tether which collects electrons from the ambient plasma directly through its exposed surface (as long as it is positively biased in respect to the plasma i.e. through the anodic segment). The tether can also collect positive ions (which get neutralized when in contact with the tether) but the currents which are obtained are much smaller due to the high mass of the ions (it is more difficult to attract the charged particles toward the electrode when they have more mass).

The EDT's could be used for de-orbiting (by generating drag) as well as for re-orbiting (by generating thrust). It all depends on the direction of the current. Naturally the electromotive force tends to induce a current which generates drag. An opposite current is only possible if an additional voltage and energy supply is used (like solar panels).

When a flexible tether is used, it can be kept straight and the force can be transferred to the S/C only because of the gravity gradient torque and the natural tendency of the tether to spin (once per orbit) which tend to keep it under tension.

This means that such a tether is naturally vertical and therefore less efficient if the spacecraft is in a high inclined orbit due to the small angle between the tether and the magnetic field. In general, a maximal drag force is obtained when the tether changes continuously its orientation so it stays parallel to the **vxB** (v: speed, B: magnetic field).

In reality the behavior of the tether is more complex. First, due to the Lorentz force distribution there is a deviation from the normal. Also because the plasma density in orbit varies almost periodically (the main period is equal to the time which takes the satellite to complete one orbit, Figure 1) and a long tether tends to oscillate at a very close frequency, the deviations can be quite important thus significantly reducing the efficiency of such a device. A few solutions were proposed for solving this problem: controlling the currents in the tether or changing the mechanical tension in the tether by modifying its length.

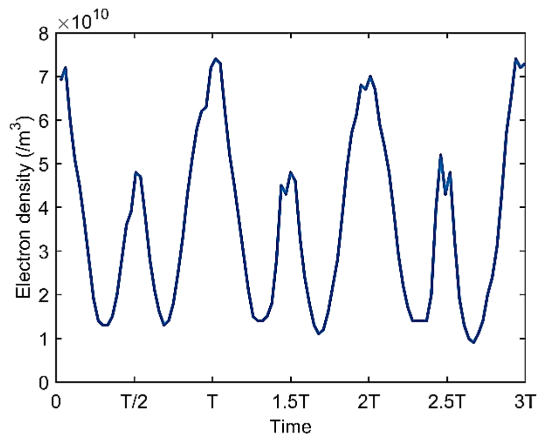

Figure 1. Electron density variation during three orbital periods (IRI-2016, 2001, 1st March, altitude = 1000km, 85° inclination, T = 1 period, starting at 12h00UT, 0°N, 0°W)

A tether, in space, is also permanently bombarded by debris of different sizes. The risk of it being cut is proportional to its length and time it stays in orbit, and of course a thinner tether can be damaged more easily.

Finally, a long and thin tether requires a complex deployment mechanism and the risk of it getting stuck or other problem is again larger when the tether is long.

We propose in the present paper an alternative EDT concept which uses a relatively stiff and short tether instead of a flexible one. This design should solve the above mentioned problems.

PROPOSED CONCEPT

The proposed thrust/drag generating system deploys one or two long curved cross section booms similar to those used for the deployment of drag/solar sails which should function as EDT tethers (EDT booms).

The deployment mechanism which can be used for this is very simple and compact. It consists of a reel on which the booms are coiled and which is actuated by a motor located inside. The booms are kept coiled by four flexible pushing spring arms which are fabricated from thin metallic sheet. This reduces the complexity of the mechanism and can easily be readapted to different sizes without the need for manufacturing additional parts.

In addition to the booms the system requires deployable solar panels. The solar energy is used for biasing a part of the tether positive in respect to the plasma for collecting electrons and for electron emission: the energy being spent in a differently depending on the technique which is used for this. Usually, in the suggested designs of EDT's there are one or two hollow cathodes which are placed at the extremities of the tether. The hollow cathodes are generating plasma clouds (these are usually small self-heating tubes containing a thermionic emitting insert and which ionize a gas which is passed through) and can be used as electron emitters as well as electron collectors. As these tethers are long the induced voltage can attain thousands of volts and the energy required for attracting electrons is provided by the magnetic field. Indeed, due to the relative motion of the satellite in the magnetic field the electromotive force could attain up to 200-300V/km. But the hollow cathodes still require energy which also would be provided most probably by solar panels.

As in the proposed design the tether is relatively short (up to a 300 meters even for large spacecraft weighting around 1 tone) most of the energy should be obtained from solar panels. In order to use large surface solar arrays they have to be also deployable. Here again there are many possibilities like for example use rolled thin surface flexible solar cells. Another possibly is to use simple solar cells which are Z folded and deployed by booms. Each cell is connected to the neighboring ones with miniature hinges and flexible electric connectors. When folded such solar arrays may be susceptible to fractures due to vibrations. In order to avoid this problem it is convenient to keep the cells under stress when stowed (burn wire + spring mechanism). For the deployment of the solar panels, the deployment could be done with a mechanism similar to that used for the EDT booms.

For a given current, due to the orientation of the magnetic field it is more convenient to use a vertical tether for low inclined orbits and a horizontal tether for higher inclined ones. For inclinations larger than 80° if a vertical tether is used, it is important to switch the direction of the current depending on the orientation of the horizontal component of the geomagnetic field. The same thing applied for a horizontal tether: the current has to be switched in this case each time the satellite crosses the magnetic equator.

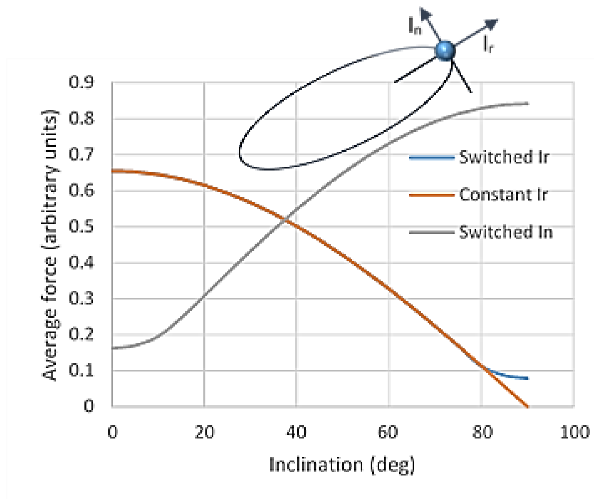

Figure 2. Average drag force per orbit (arbitrary units) for horizontal and vertical tethers as a function of the orbit inclination (1000km altitude)

Electron collection

The tether collects electrons in an orbital motion limited regime. In such case the collected current density is approximately proportional to the tether cross section perimeter, the plasma density and the square root of the bias voltage.

Electron emission

Different techniques could be used for electron emission. First of all we tried to avoid the use of an expellant which is required for example by hollow cathodes. Different techniques were investigated: photoemission, thermionic emission and in the end it was decided to use small thermionic emitters (dispenser cathodes) placed at each extremity of the deployed EDT booms.

System scaling

The size of the system directly depends on the mass of the satellite and on its orbital radius. In LEO orbits in order to be able to change the orbit radius by a few hundred km in 5 years an average force of the order of 5μN/kg is required.

The average force obtained with the proposed system is proportional to the length of the EDT booms squared. One could also estimate the required surface of the solar arrays (Table 1).

Table 1: Scaling of the drag/thrust generating system

Spacecraft mass (total mass)	Total length of the EDT booms	Solar array surface (total surface of the solar cells)
10 kg	30m	$0.25m^2$
50 kg	70m	$0.6m^2$
500 kg	210m	$2m^2$
1 tone	300m	$2.7m^2$

The performance of the system depends on the altitude and solar activity. One can estimate the generated force by using the IRI-2016 model (Figure 3). It is easy to show that the proposed system could change the radius of the orbit from an altitude of 1000km by 200km in around 6 years.

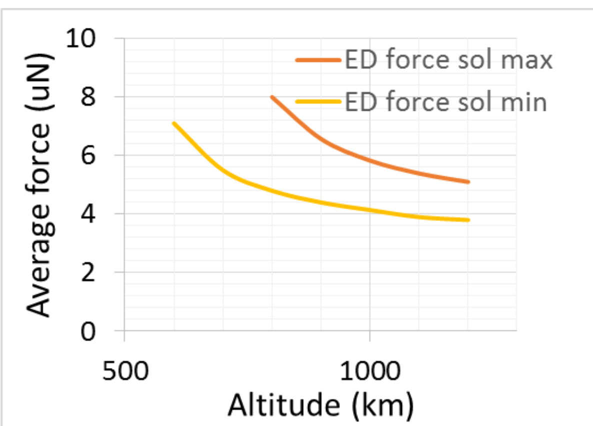

Figure 3. Average force which can be obtained with the proposed propellant-less system as a function of altitude (for different solar activities 2002 vs 2008, equatorial orbits)

The electrodynamic forces are decreasing with the altitude because of the exponential variation of the plasma density and the decrease of the strength of the geomagnetic field. One could however still use the electrostatic interaction between the booms and the plasma in order to generate force (the e-sail concept). This idea will be discussed in another paper.

DESIGN OF A PROTOTYPE

A prototype of the above described system has been designed and different subsystems have been manufactured (Figure 4-Figure 6).

The prototype should help validate the proposed concept but also demonstrate the possibility of deploying long booms and the use in an efficient way of thermionic emitters in an EDT system.

CONCLUSIONS

We present in this paper a new concept of a drag/thrust generation system which could be used in satellites for orbital relocation or de-orbiting. The system employs stiff booms which act as electrodynamic tethers passively collecting electrons from the ambient plasma and emitting electrons with special thermionic emitters (dispenser cathodes). The system requires a source of energy and for this deployable solar arrays are used.

A prototype which will be integrated into a 6U CubeSat structure is currently being built and different subsystems are being tested.

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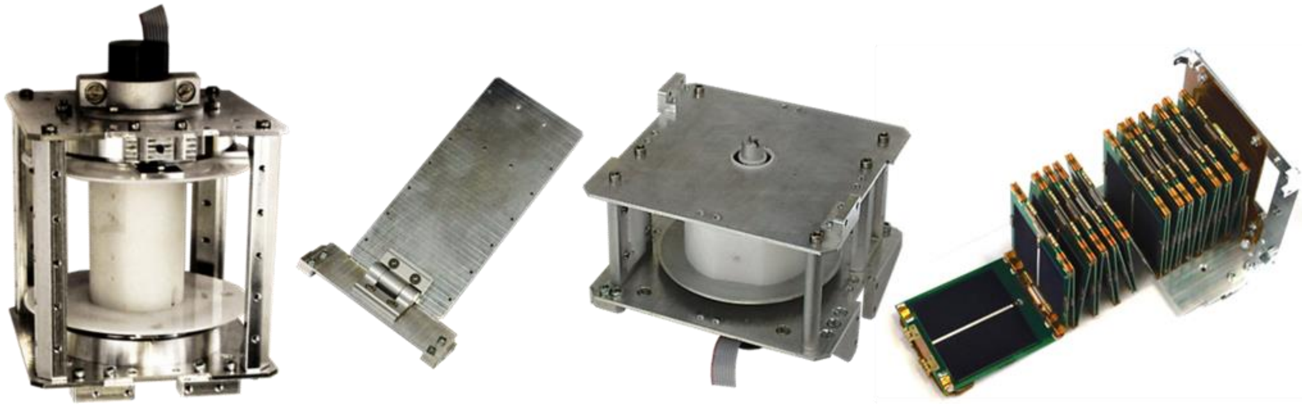

Figure 4. Different manufactured parts of the prototype: EDT booms deployment mechanism, structure side panels, deployment mechanism used for the deployment of the solar arrays, Z folded deployable solar arrays

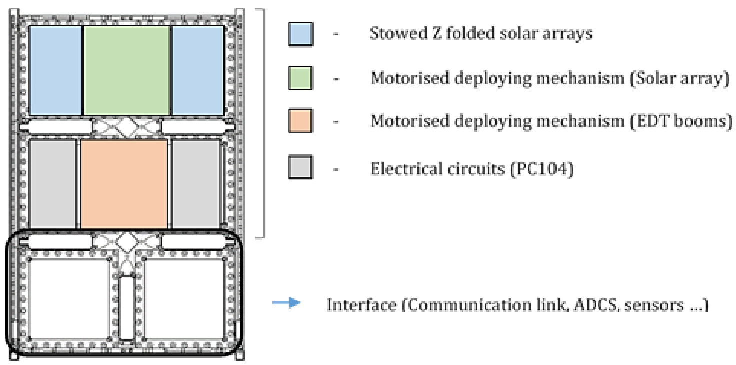

Figure 5. Location of different prototype subsystems inside the 6U structure

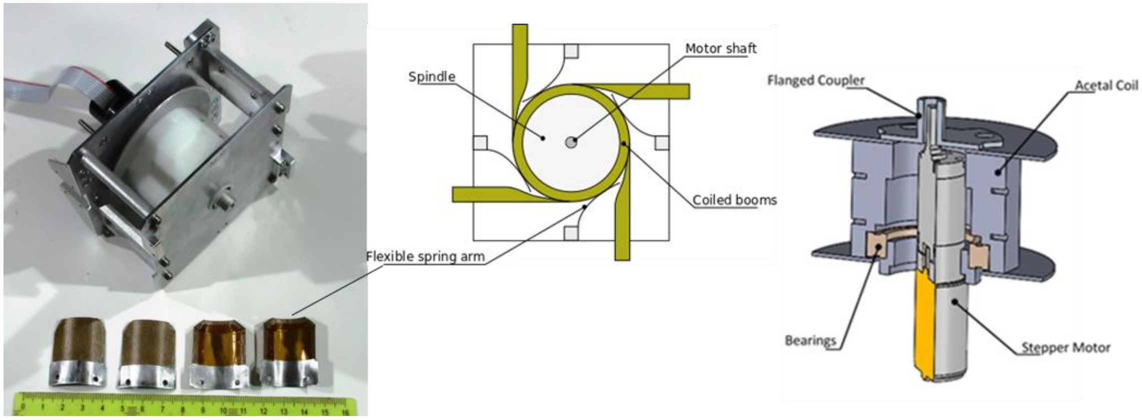

Figure 6. Mechanism used for the deployment of the solar arrays in the prototype