Electric Solar Wind Sail Propulsion System Development

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The electric solar wind sail (E-sail) was invented in 2006 and has thereafter been developed rapidly. This paper is a progress report of E-sail technical development as it stands in August 2011. We conclude that E-sail development is well underway, no major problems have been encountered so far and a revolutionary level of performance (1 N infinite Isp thrust from 100-200 kg package) seems realistic.

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Nomenclature

dF/dz = E-sail thrust per unit tether length
ϵ_0 = vacuum permittivity
m_p = proton mass
n_0 = solar wind plasma density
$P_{\rm dyn}$ = solar wind dynamic pressure
r = solar distance
r_w^* = effective electric radius of tether
R = radius of electron sheath
v = solar wind speed
V_0 = tether voltage
V_1 = stopping voltage of solar wind protons

I. Introduction

Finding fast and economical ways of moving around in the solar system is a long-standing goal of space technology. The electric solar wind sail[1,2] (E-sail) is a novel in-space propulsion method that was invented in 2006 for addressing this goal. It proposes to tap the natural solar wind momentum flux for space propulsion with the help of long, thin, charged and centrifugally stretched tethers that deflect solar wind proton trajectories by the electrostatic repulsion. As such, it can be thought of as a "natural ion thruster" that does not have to carry propellant and that needs only modest onboard power to keep its tethers charged. According to detailed analysis[3], an E-sail capable of producing 1 N continuous thrust at 1 AU distance, weighing 100 kg and using 700 W of power is possible to build with existing technology. Such an E-sail would have about 2000 km total tether length, comprising e.g. 100 tethers each 20 km long. The produced thrust scales as $1/r$ and the power requirement as $1/r^2$ where r is the distance from the sun. The employed maximum tether voltages are 20-40 kV. With these performance numbers, the lifetime integrated total impulse per propulsion system mass of the E-sail is 100-1000 times higher than for chemical rockets and ion engines in a favourable case (e.g., 10-year mission that operates within few AU from the Sun). For other missions the relative benefit may be less, but still very significant. The baseline 1 N E-sail would allow us to take a 1000 kg payload almost anywhere in the solar system in a reasonable time[4,5] (comparable to or faster than fastest traditional methods), to accelerate a smaller 200 kg payload at over 50 km/s out of the solar system[6] or to keep a payload in a non-Keplerian orbit indefinitely[7]. Besides solar system science, the capabilities of the E-sail could be used in the future also for novel commercial applications such as asteroid resource utilisation or direct propulsive deflection of Earth-threatening asteroids[8,9]. Despite the fact that the natural solar wind is highly variable, the E-sail thrust varies much less and the system is surprisingly accurately navigable[10].

II. E-sail overall configuration

Figure 1 shows the current baseline spin-stabilised E-sail configuration, consisting of main tethers, stretched auxiliary tethers and "Remote Units". A number of conductive main tethers are deployed from reels located on the main spacecraft. To keep the main tethers apart during flight despite solar wind induced oscillations, the tips of the main tethers are connected by auxiliary tethers made of nonconducting material. At each main tether tip there is one Remote Unit, containing the neighbouring auxiliary tether reel(s) and a small thruster for initially spinning up the system and optionally for adjusting the spin later in flight. While several E-sail geometric variants have been considered and are possible, the one shown in Fig. 1 is our current baseline configuration.

The main spacecraft has an electron gun or guns for shooting out electrons at high energy ($\sim 10-40$ kV) and thus to keep the tethers highly positively charged during propulsive flight. Individual fine tuning of the main tether voltages is used for turning the orientation of the tether spin plane. By tilting the spin plane up to $60^{\rm o}$ one can vector the obtained solar wind thrust by up to $\sim 30^{\rm o}$.

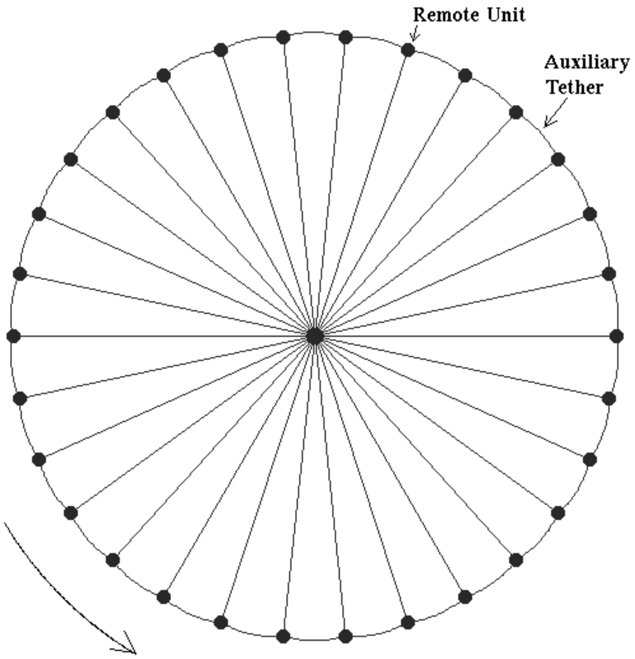

Figure 1. Baseline E-sail configuration with Remote Units and stretched auxiliary tethers.

Approximate E-sail thrust per unit tether length is given by[3]

$$\frac{dF}{dz} = \frac{2.2}{\log(R/r_w^*)}(V_0 - V_1)\sqrt{\epsilon_0 P_{\rm dyn}} \tag{1}$$

where V_0 is tether voltage, $V_1 \approx 1$ kV stopping voltage of solar wind protons, $P_{\rm dyn} = m_p n_0 v^2 \approx 2$ nPa is solar wind dynamic pressure, $R \approx 100$ m is the radius of the electron sheath that develops around the tether (which is not constant, but since the dependence on it is logarithmic an order of magnitude estimate suffices) and $r_w^* \approx 1$ mm is the effective electric width of the multi-wire tether. A typical thrust per unit tether length value is $dF/dz = 0.5$ μN/m.

If one of the main tethers breaks, it is jettisoned from both ends and the mission continues. The Remote Unit thrusters act as natural backups of each other so they are not single-point failure points either. A broken auxiliary tether would cause severe malfunction, however, because the tether rig would then collapse to one side. To eliminate this possibility, large safety factors are used when designing the auxiliary tethers for pull strength and micrometeoroid tolerance.

III. Status of technical development

A. Main tethers

The main tethers need to be electrically conducting, they need to withstand the centrifugal pull, their surface area should be as small as possible to minimise their gathered electron current from the plasma and they need to survive in the space environment (vacuum, temperature changes, micrometeoroids and radiation) throughout the mission. Concerning main tether strength, the performance (thrust versus mass) of an optimally designed E-sail is approximately linearly proportional to the tensile strength over mass of the tethers. The current baseline is to load the main tethers at 0.05 N level which allows one to build a 1 N E-sail weighing ~100-200 kg.

Our main tethers are made of 25-50 μm aluminium wires. Four wires are bonded together at regular intervals (Fig. 2) to produce a tether with enough redundancy that it survives 5 years in space at 2000 km total length (1 N E-sail) with 1 % failure probability. Several tether geometries are possible, including the well-known "Hoytether" as well as our "Heytether" (Fig. 2). The wires are bonded together by a commercial

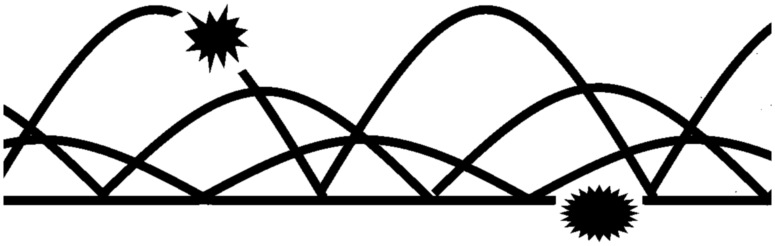

Figure 2. Schematic shape of 4-wire "Heytether" consisting of straight 50 μm base wire and three 25 μm loop wires of different heights to maximise tolerance towards micrometeoroid hits. The loop heights are typically 1-2 cm. Stars illustrate some micrometeoroid impacts that the tether is designed to tolerate.

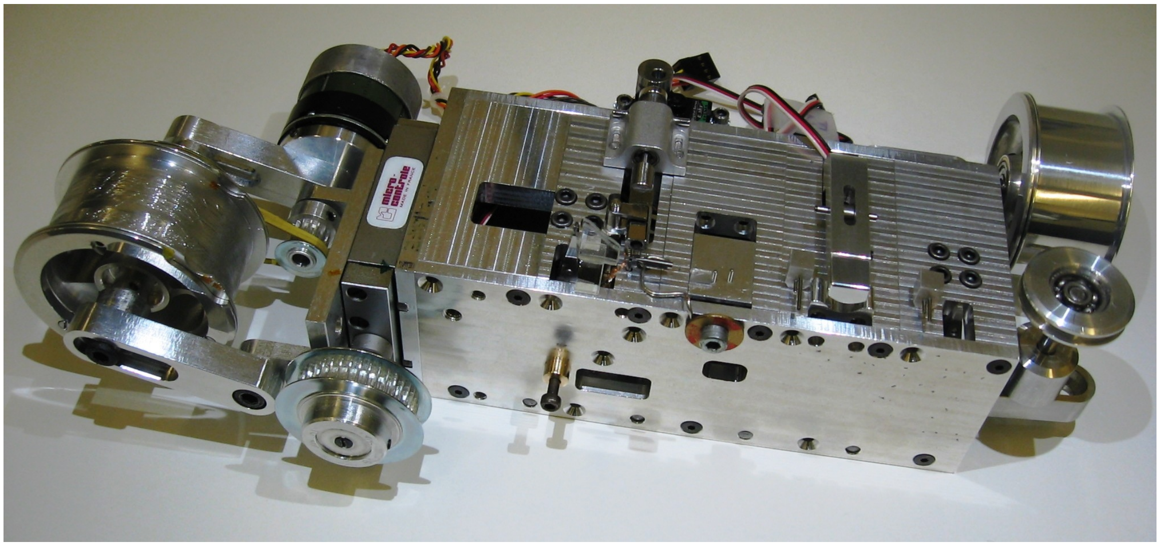

Figure 3. Tether factory that was used to produce the tether in Fig. 4. The length of the factory is 31 cm.

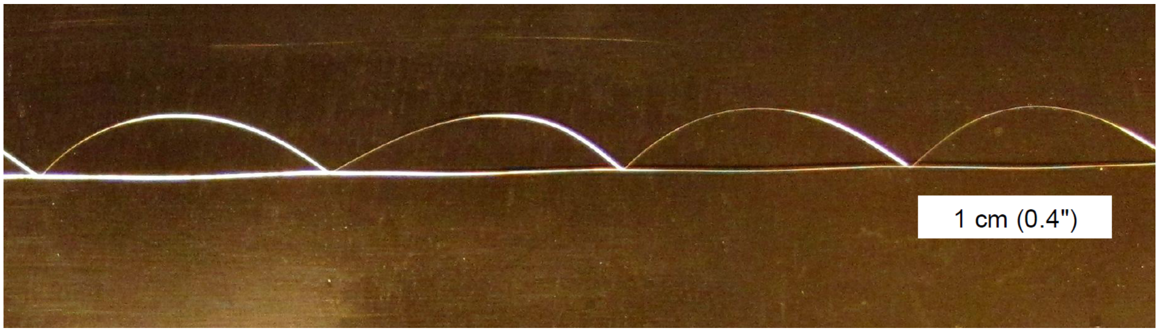

Figure 4. Closeup view of produced 10 m long 2-wire Heytether sample.

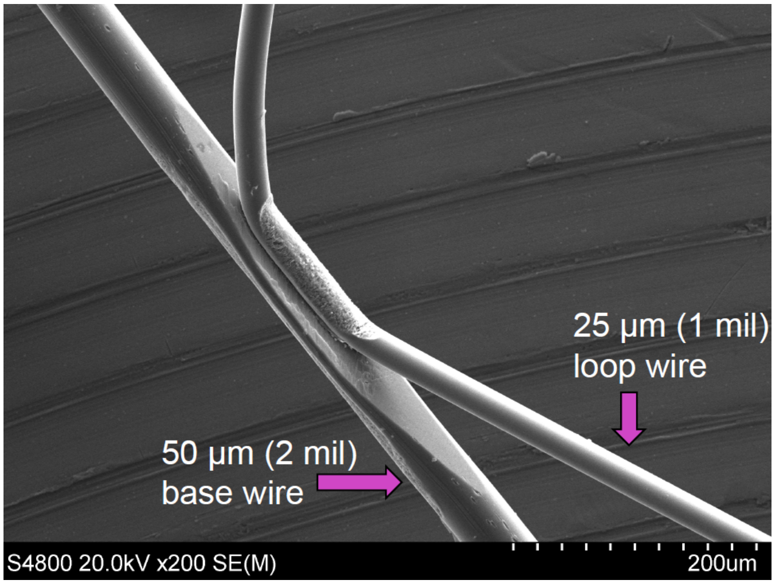

Figure 5. Scanning electron microscope image of a single ultrasonic wire bond of the tether shown in Fig. 4. Flattening of the 50 μm base wire was made before bonding.

ultrasonic bonder machine using a special jig (automatic tether factory, Fig. 3) for flattening the base wire before bonding, for holding the wires firmly in place during bonding and moving the wires to the next bonding position. Fig. 4 shows a sample of a 10 m 2-wire tether produced by the factory. A 4-wire tether resembling Fig. 2 has been produced at 30 cm length (not shown). Figure 5 shows an electron microscope image of a single ultrasonic wire-to-wire bond. The measured parallel pull force of the produced tether bonds is 0.114 ± 0.008 N which exceeds the adopted 0.05 N design goal by a sufficient margin.

B. Electron gun

A full-scale E-sail needs an electron gun producing maximum ∼20-40 keV energy electron beam with maximum ∼50 mA current. The current and voltage must be separately controllable between near zero and the maximum value. The maximum power requirement is ∼0.5-1 kW. An electron gun meeting these specifications can be designed using conventional hot cathode techniques (Zavyalov et al., unpublished report, 2006).

In the ESTCube-1 and Aalto-1 CubeSat test missions that are described below, however, electric power for heating even a small cathode is not conveniently available on the spacecraft. Consequently, for the CubeSat test missions, a cold cathode miniature electron gun is being developed in the University of Jyväskylä Accelerator Laboratory. The gun is based on electron field emission from a cold nanographite surface containing many sharp protruding edges one or a few atomic layers thin. As a puller electrode (anode), a metal wire mesh is used.

C. Remote Units and auxiliary tethers

The Remote Units on the main tether tips are small autonomous mini-spacecraft hosting the auxiliary tether reels and small thrusters for initiating the spin and possibly controlling it during propulsive flight (Fig. 6). The Remote Units also host optical beacons that are observable from the main spacecraft so that the flight algorithm on the main spacecraft can monitor the instantaneous pointing direction of each main tether. The current baseline is that the auxiliary tether is made of 3 cm wide and 12.6 μm thin polyimide (Kapton) sheet which is suitably perforated to give it a certain elasticity and to reduce its weight. The amount of elasticity needed is determined by trial and error method from a dynamical simulation in realistic solar wind conditions and finding the value of auxiliary tether elasticity which minimises unwanted oscillations. For a baseline full-scale E-sail consisting of 100 tethers each 20 km long, each auxiliary tether is 1250 m long. This amount of auxiliary tether weighs 0.2 kg if 70% perforated and it can be reeled on two 10.5 cm diameter reels

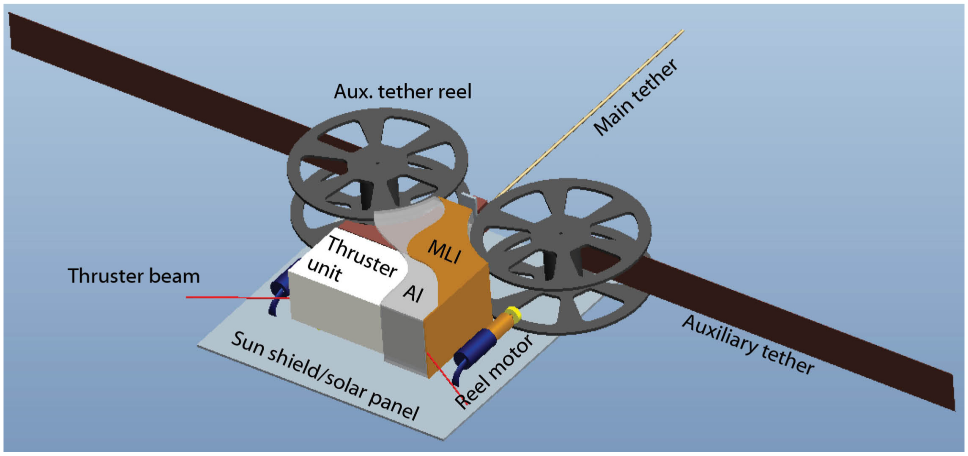

Figure 6. Baseline Remote Unit design. Sun direction is below.

per Remote Unit. The goal for the dry mass of the Remote Unit (excluding tether and excluding propellant) is 0.5 kg.

The minimum impulse per Remote Unit that is required to spin up the system is about 30 Ns if one assumes target 0.05 N main tether tension and 0.7 kg combined mass of the Remote Unit and auxiliary tether. This impulse can be obtained from a cold gas or evaporative thruster which is under development at Nanospace. However, if one also needs to perform propulsive tuning of the spinrate during flight, the impulse requirement may become higher. For such purpose, a miniature ionic liquid FEEP thruster is under development at Alta[12] that can produce up to 2000 Ns total impulse. A need for propulsive spinrate management may arise from Coriolis acceleration due to the spacecraft orbiting the Sun with its powered E-sail inclined with respect to the radial direction.

IV. Planned test missions

Our plan is to first demonstrate single Heytether deployment and to measure the strength of the E-sail effect in low Earth orbit (LEO) by two CubeSat missions, then fly a solar wind test mission that demonstrates modification of spacecraft trajectory by E-sail propulsion.

A. ESTCube-1 and Aalto-1

ESTCube-1 is a single-unit CubeSat ($10 \times 10 \times 10$ cm^3, 1.3 kg) that will deploy one 10 m long Heytether and attempt to measure the E-sail force acting on it when the tether is biased 500 V positively and negatively with respect to the surrounding ionospheric plasma at the satellite's orbital altitude of 600-700 km. The positive polarity tether mode (relevant to the E-sail) is created by a small onboard electron gun being developed at University of Jyväskylä Accelerator Laboratory. The negative tether mode is relevant to the plasma brake[13,14]. The expected $\sim$1 μN E-sail force is measured by turning the tether voltage on and off in a synchronous way with the satellite's rotation. In this way, the E-sail force can be used to alter the satellite's and tether's spinrate. The change in the spinrate should become noticeable and even large after some hours of experiment. ESTCube-1 is currently under construction and the planned launch is at end of 2012 and the E-sail experiment is its main payload.

Aalto-1 is a 3-unit CubeSat ($10 \times 10 \times 30$ cm^3, 4 kg). It will include a similar E-sail experiment than ESTCube-1 (except that the planned tether length is 100 m) and it is planned to be launched in 2013-2014.

B. Solar wind test mission

An stripped-down E-sail configuration that can be tested in the solar wind to demonstrate controlled propulsive flight and that is dynamically similar to a full-scale E-sail would consist of three main tethers plus their interconnecting auxiliary tethers, i.e. like Fig. 1, but with only three main tethers. If the main tether length is selected to be 720 m, then the auxiliary tethers become the same length (1250 m) as in the baseline full-scale mission so that the same Remote Units design can be used in demonstration and full-scale missions with no wasted space on the reels. Such a mission would contain 2.2 km total main tether length and it would produce about 1 mN E-sail thrust, giving ∼300 m/s delta-v per year if the spacecraft's total mass is 100 kg.

The ∼100 kg class test mission could be launched, for example, by geosynchronous transfer orbit (GTO) piggyback combined with a kick motor that injects it to nearly parabolic orbit with respect to Earth, so that the spacecraft recedes slowly from Earth but remains in its vicinity (less than 2 million km, say) for ∼6-12 months. This is ample time to carry out E-sail thrust experiments in various solar wind conditions. The target of the mission is to measure the E-sail force accurately in different solar wind conditions (the solar wind properties prevailing in Earth's vicinity can be obtained from other spacecraft such as ACE and SOHO) and to demonstrate controlled spinplane manoeuvres and propulsive flight based on the solar wind thrust effect – and to do this using a construction which is scalable to 1 N thrust level.

V. Conclusion

The development of E-sail propulsion is well underway and no major problems have been encountered thus far. It seems that no further breakthroughs are needed for a revolutionary level of performance (1 N infinite Isp thrust from 100-200 kg E-sail device).

Acknowledgments

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