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Electric sail, photonic sail and deorbiting applications of the freely guided photonic blade

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ABSTRACT

We consider a freely guided photonic blade (FGPB) which is a centrifugally stretched sheet of photonic sail membrane that can be tilted by changing the centre of mass or by other means. The FGPB can be installed at the tip of each main tether of an electric solar wind sail (E-sail) so that one can actively manage the tethers to avoid their mutual collisions and to modify the spin rate of the sail if needed. This enables a more scalable and modular E-sail than the baseline approach where auxiliary tethers are used for collision avoidance. For purely photonic sail applications one can remove the tethers and increase the size of the blades to obtain a novel variant of the heliogyro that can have a significantly higher packing density than the traditional heliogyro. For satellite deorbiting in low Earth orbit (LEO) conditions, analogous designs exist where the E-sail effect is replaced by the negative polarity plasma brake effect and the photonic pressure by atmospheric drag. We conclude that the FGPB appears to be an enabling technique for diverse applications. We also outline a way of demonstrating it on ground and in LEO at low cost.

1. Introduction

The spinning electric solar wind sail (E-sail) [1–3] and the spinning heliogyro photon sail [4,5] have been proposed for propellantless interplanetary travel. Likewise, various LEO deorbiting devices based on Coulomb drag [8,9] and atmospheric drag [10,11] have been proposed for mitigating the space debris problem by deorbiting satellites after their mission is complete and by deorbiting already existing junk objects by attaching braking devices to them.

In this paper we consider a freely guided photonic blade (FGPB) which is part of a spinning system so that it is kept stretched by the centrifugal force. In ground-based conditions we can mimic the centrifugal force by gravity (Fig. 1a). If a ballast mass is moved sideways (Fig. 1b and c), a difference between the centre of mass and centre of photon pressure is created and consequently the photon pressure starts to turn the blade about the vertical axis. This gives a simple way to control the blade's orientation with respect to sunlight and thus to control the direction of the photonic thrust vector.

Throughout the paper we treat the heliogyro photonic blades as rigid objects. Although the blade is in reality free to bend and is not made of rigid material, the rigid body approximation is valid if the shape of the blade does not differ markedly from a planar surface. This is the case if the membrane is lightweight in comparison to the mass of the remote unit which controls it or if the spin of the sail is fast so that the centrifugal force acting on the blade is much larger than the actuated part of the photon pressure force. If the blade is made very long and if it is actuated from either end, it tends to twist in response to actuation instead of tilting uniformly. Problems due to twisting and bending increase in severity if the blade's aspect angle K[1] (length versus width) is made larger. In the formulas of

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[1] See Nomenclature.

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Nomenclature

A	heliogyro total blade area
A_p	area of largest inscribed disk inside polygon
d	blade thickness
F	photonic thrust force (acting on single blade)
F_{cf}	centrifugal force (acting on single blade)
h, h'	blade width (also called height), plain and projected
I	inertial moment (about long axis) of blade
K	heliogyro blade aspect ratio (length per width)
k	$=F_{cf}/F$, centrifugal force per photonic force
L	blade length
L_t	tether length
m_0	remote unit mass of novel type heliogyro blade
m_b	mass of single novel type heliogyro blade
N	number of blades or tether–blade systems
P_{rad}	radiation pressure
R	radius of stowed configuration or spacecraft
r	radial distance (from spacecraft or from sun)
r_R	blade storage reel outer radius
V	centrifugal potential energy of blade
x	horizontal coordinate
y	vertical coordinate, actuated shifting of centre of mass of blade
α	tilting angle of novel type heliogyro blade
ω	angular rotation rate of novel type heliogyro
σ, σ'	mass per area of blade, plain and projected
τ, τ'	torsional torque, plain and actuated
E-sail	electric solar wind sail, electric sail
FEEP	field effect (or field emission) electric propulsion
FGPB	freely guided photonic blade
ITAR	international traffic in arms regulations, set of U.S. regulations
LCD	liquid crystal display
LEO	low Earth orbit
RU	remote unit, autonomous device at the tip of the each E-sail tether
TRL	technical readiness level

this paper the aspect ratio K appears as a free parameter. This allows us to e.g. compare the packing efficiency of different sail concepts in a regime where both are configured with the same aspect ratio.

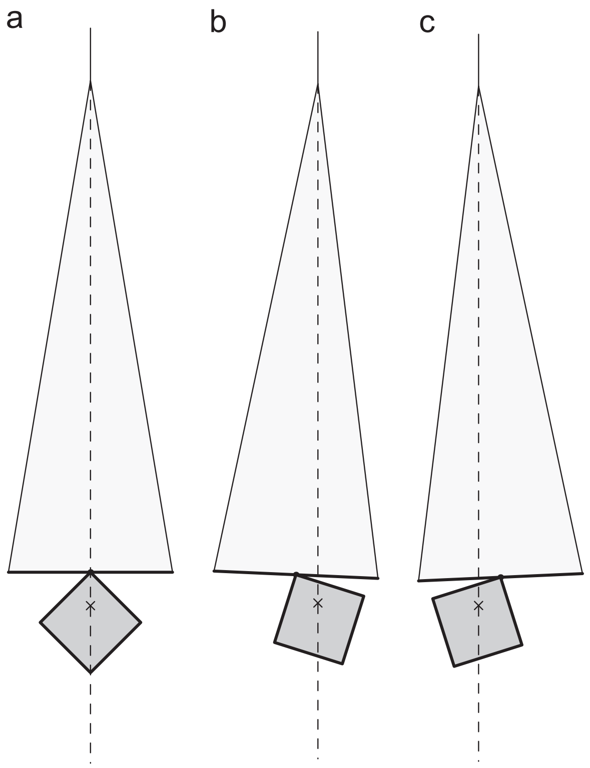

Fig. 1. Photonic blade hanging in gravity field. Moving the ballast mass right (b) or left (c) changes the centre of gravity (×) of the system so that a photonic torque about the vertical axis gets applied to the blade and it starts to turn about the vertical axis.

The structure of the paper is as follows. We first treat the traditional photonic heliogyro and its issues, then consider the improved FGPB heliogyro variant and then consider a scalable and modular E-sail by adding tethers to the heliogyro. After that we outline analogous LEO deorbiting applications for both E-sail and heliogyro, discuss briefly FGPB implementation and demonstration options and close the paper with a summary and outlook.

2. Review of traditional heliogyro

The traditional heliogyro [4,5] (Fig. 2) is a type of solar photon sail which has several benefits compared to three-axis stabilised square sails. Recently the heliogyro concept

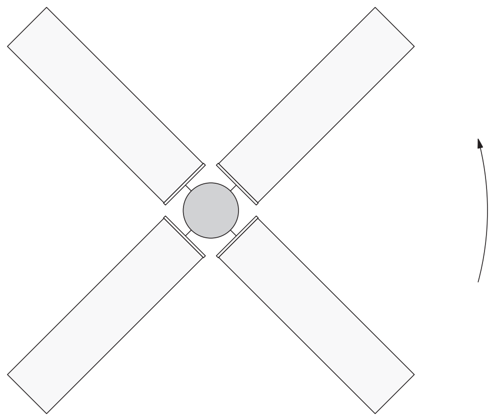

Fig. 2. Traditional spinning heliogyro photon sail, in this case with four blades. The blades are initially deployed from wide rotating reels by the centrifugal force. Angular momentum of the sail can be changed by photonic torque resulting from blade tilting by mechanical actuators on the main spacecraft. Said photonic torque can also be used to turn the spin plane of the sail which enables control of the thrust vector direction.