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SPACE DEBRIS REMOVAL WITH AN ION BEAM SHEPHERD SATELLITE: DYNAMICS AND CONTROL

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Among the different strategies to actively remove space debris from low and geostationary Earth orbits, it has been recently proposed to use a highly collimated neutralized plasma beam pointed at a generic debris from a nearby "shepherd satellite" to perform a contactless deorbiting or re-orbiting manoeuvre. A key aspect of such removal concept is the need to stabilize the relative position of the co-orbital debris-shepherd system throughout the orbital transfer manoeuvre and prevent accidental collisions. In the present article we report 3-D numerical simulations of the IBS relative dynamics and control problem.

I. INTRODUCTION

After half a century of space activities more than 5800 tons of technogenic material has been left in earth orbit in form of active and defunct satellites, rocket upper stages, and fragments of these. More than 40 % of this mass has been placed in low earth orbit (LEO), by far the most crowded region around Earth. According to recent studies a collision between two large space objects in LEO is likely to occur every few years and the possibility of an escalation of the number of collisions following a chain reaction has been speculated [1].

While the good practice of deorbiting newly launched satellites before the end of their operational lifetime will have a beneficial impact in terms of collision risks it has been pointed out that in order to stabilize the growth of debris fragments to a sustainable level is will be necessary to actively deorbit 5 to 10 existing large-size space debris per year [2-3].

Among the different challenges involved with the active removal of dead satellites and upper stages stands the difficulty in delivering the deorbiting or re-orbiting momentum to the target. The most intuitive mean to do that is to have an active spacecraft docking with the debris and performing the required modification of the orbit semi major axis. The problem is that docking with a non-cooperative, poorly known object with a possibly tumbling or spinning motion is technologically very complicated and risky. A promising solution to get around this difficulty is to transfer the momentum remotely using the exhaust of an ion thruster pointed at the target from a nearby shepherd satellite, as it has been recently proposed [4-9]. The beam would transfer enough momentum to modify the orbit and/or attitude of the debris from a safe distance in a controlled manner without the need for docking.

Although in principle conceptually simple, the proposed removal approach involves new and interesting challenges from the dynamics and control point of view. Most importantly, the debris shepherd and the space debris should be simultaneously de-orbited (or re-orbited) in a controlled and reliable way, keeping a safe distance between each other and avoiding collisions. This implies not only the need for advanced sensors, actuators and control strategies, but also, and first of all, the implementation of accurate models describing the dynamic interaction between the debris and the plasma beam. The present article studies such interaction and their implications on the relative position control problem of the debris with respect to the shepherd satellite.

II. THE ION BEAM SHEPHERD (IBS)

The ion beam shepherd concept (IBS) [4] is a novel use of space electric propulsion in which the plasma accelerated by an ion thruster (or similar plasma propulsion device) is directed against the surface of a target object to exert a force (and a torque) upon the target from a distance of a few times its size (Fig.1). The force transmitted comes from the variation of momentum of the plasma ions (typically xenon) impacting against the surface of the object and penetrating its outermost layers before being stopped.

This simple idea, in which the accelerated plasma is used to produce an *action* rather than a *reaction*, can be used to remotely manoeuvre objects in space without physical contact (docking). A promising application is found in the area of active removal of space debris, which are non-cooperating targets that can be extremely difficult to dock as they can exhibit chaotic attitude motion.

During a typical LEO deorbiting/re-orbiting mission the IBS would rendezvous with the target debris and, while co-orbiting at constant distance in front of the latter, have one of its ion beams constantly pointed at its surface to produce a small continuous drag force able to change the orbit semi major axis by a few hundreds of kilometres in a few weeks or months [4].

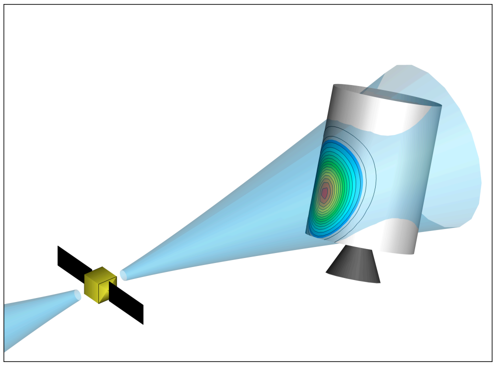


Fig. 1: Schematic of ion beam shepherd (IBS) satellite.

Once the mission is completed the IBS would manoeuvre itself towards another target and repeat the operation until exhausting the available propellant.

A critical aspect of the operation is the need to have a stable relative position between the IBS and the target debris throughout the whole manoeuvre, which will need an ad hoc guidance, navigation and control system.

III. DEORBITING OR REORBITING?

Following the recent event of the uncontrolled reentry of the defunct 6-ton UARS satellite, concern has been raised about the casualty risk connected with the reentry of large satellites and upper stages. While aluminum, the most abundant element in space hardware, is very unlikely to survive reentry, other spacecraft parts, such as titanium parts may do.

This fact further complicates the active debris removal operation by placing the additional constraint of having a targeted re-entry for the largest debris. Because targeted re-entry cannot be performed with low-thrust propulsion hardware the IBS concept can clearly not fulfil such constraint.

On the other hand the risk of uncontrolled re-entry can be eliminated completely by just not having the debris re-enter in the atmosphere. The alternative is to move the debris to a higher cemetery orbit where the density of space objects is so low to not pose any significant collision risk. At present, the Globalstar constellation operating around 1400 km altitude is routinely disposed to an orbit near or beyond 2000 km altitude. For an initial altitude of 1000 km the cost of transferring the debris to a 2000-km altitude orbit instead that to a 300-km one would be just 20% higher. On the hand for an initial orbit of 800 km altitude the re-orbiting option would be twice as expensive.

The possibility of recycling space debris parts in the future could further strengthen the re-orbiting option.

IV. THE ION BEAM INTERACTION SIMULATOR (IBIS)

The physical interaction between a solid body and an ion-beam, as described in reference [7-9], has been modelled numerically and inserted into an in-house software called IBIS (Ion Beam Interaction Simulator).

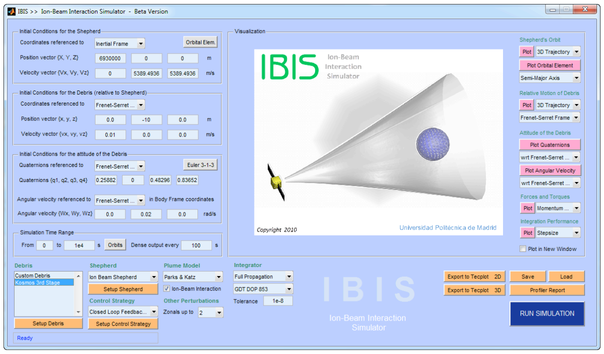
IBIS is a powerful simulation tool developed to deal with the IBS concept, where the interaction of the thruster ion beam and the debris must be reliably estimated and combined with the dynamical equations of the debris relative and attitude motion in a generic orbit environment. The necessity of such a tool became evident as the physical and engineering complexity of the concept began to take form, calling for numerical methods as the most convenient way to further develop the concept.

The IBIS software has become an important working tool for the tuning, testing and validation of physical models, the study, analysis and conceptual design of the IBS concept, as well as to evaluate and qualify the performance of the overall system, understand the impact of certain design parameters, and optimise particular features such as control laws, design parameters and deorbiting strategies.

The variety of features implemented demand for a user friendly working environment, high computational cost restraints, interoperability issues with previously developed computing libraries and third party visualization software. In addition, the need for making internal subroutines and computational kernel easily available for other scripts outside IBIS, led to the use of hybrid programming techniques as the most efficient way to achieve all this. Thus, IBIS has been implemented by using up to three different programming languages:

Matlab: The core of the program has been implemented in Matlab, which allows for fast prototyping and use of Matlab's optimised and tested built-in functions, along with the convenience of an interpreted language. Matlab's working environment also allows for the use of object-oriented programming and the quick development of a Graphical User Interface (GUI) for a faster and easier usage of IBIS, both for entering input data and parameters, and for the analysis and visualization of results.

Fortran: The high computational cost of reliably calculating the forces and torques upon the debris caused by the interaction with the plasma plume suggested compiling the most cost-expensive parts of the IBIS Software's computing kernel in order to speed up the runtime performance. For this purpose a code using Fortran 2008 standard was employed, compiled as a MEX function to assure the compatibility with Matlab. As an additional feature, this Fortran code was parallelized by using OpenMP 3.0, which enhances the performance of IBIS when run in Work Stations and computers with multi-threading capabilities


IBIS >> Ion-Beam Interaction Simulator - Beta Version

Initial Conditions for the Shepherd
Coordinates referenced to: Inertial Frame
Position vector {X, Y, Z}: 6930000, 0, 0 m
Velocity vector {Vx, Vy, Vz}: 0, 5389.4936, 5389.4936 m/s

Initial Conditions for the Debris (relative to Shepherd)
Coordinates referenced to: Frenet-Serret ...
Position vector {x, y, z}: 0.0, -10, 0.0 m
Velocity vector {vx, vy, vz}: 0.01, 0.0, 0.0 m/s

Initial Conditions for the attitude of the Debris
Quaternions referenced to: Frenet-Serret ...
Quaternions {q1, q2, q3, q4}: 0.25882, 0, 0.48296, 0.83652
Angular velocity referenced to: Frenet-Serret ... in Body Frame coordinates
Angular velocity {Wx, Wy, Wz}: 0.0, 0.02, 0.0 rad/s

Simulation Time Range
From 0 to 1e4 s Dense output every 100 s

Debris: Custom Debris, Kosmos 3rd Stage
Shepherd: Ion Beam Shepherd
Control Strategy: Closed Loop Feedbac...
Plume Model: Parks & Katz
☑ Ion-Beam Interaction
Other Perturbations: Zonals up to 2
Integrator: Full Propagation, GDT DOP 853
Tolerance: 1e-8
Ready

Fig. 2: IBIS graphical user interface

ANSI C: IBIS also takes advantage of the home-made "ODE.2" library implemented in C and compiled as a Matlab MEX function. The library ODE.2 gathers a bunch of fast, reliable and efficient implementation of 15 different numerical integrators for ordinary differential equations, most of which can be used by IBIS. This library has been developed by our research group during past projects and has been fully tested and validated.

The IBIS Software has been structured following the same philosophy as CFD or FEM codes, i.e. it is divided into three sequential steps: pre-processing, simulation and post-processing.

The pre-processing is fed with user provided data and parameters for the simulation. This data is read from the GUI and/or external data files and collected for pre-processing. The pre-processing consists in three aspects:

1) Parameters, constants and setups are stored for the simulation, including the parameters for the ion thruster (user given or selected from IBIS thruster database)
2) Initial conditions for the orbital motion of the ion beam shepherd, the relative orbital motion of the debris and the attitude dynamics of the debris can be provided in coordinates of different reference frames.
3) A mesh of the debris in created from the geometry of the debris (user-given or selected from an internal IBIS debris database) and meshing options provided by the user. IBIS has automated mesh generators based on triangular or quadrilateral finite elements, allowing meshes for general geometries.

IBIS can mesh any geometry based on a user provided set of solid spherical harmonics.

The simulation or core computation is the numerical integration of the governing equations of the motion. Currently a total amount of 15 equations are integrated altogether, which can be broken down as follows:

- Debris-Shepherd Relative Orbital Dynamics (6 Eqs.)
- Shepherd Orbital Dynamics, considering the perturbed two-body problem (6 Eqs.)
- Attitude Dynamics of the Debris, handling the rotational state in quaternions to avoid singularities and provide robustness (7 Eqs.)

These equations need, at each integration step, the values of the force and torque vectors upon the debris due to the plume-debris interactions, which can be calculated with any of the self-similar models of chapter 2. It also requires the values of the control forces acting upon the shepherd, which are provided by an adequately tuned control strategy, fully customizable within the IBIS software.

Finally, when the numerical integration is over the post-processing just takes the results of the simulation and projects the coordinates of the trajectories onto all available reference frames (Inertial, Frenet-Serret, Local Vertical - Local Horizontal, Jet and Body), and the same for attitude quaternions and angular velocities. Additionally, derived data is computed from the solution, such as orbital elements, momentum transfer efficiency, plume-debris interaction forces and torques, control forces, etc.

After the post-processing is over, the user is able to visualize all the computed data from within the IBIS graphical interface. The results can be saved for later study or even exported to plain text files for further post-processing. Additionally, animated video sequences can be obtained by exporting the results into adequately formatted files.

V. NUMERICAL SIMULATIONS

Equations of Motion

After linearising the local gravity field around the shepherd spacecraft orbital position the equations of motion governing the evolution of the debris relative position $\boldsymbol{\rho}$ with respect to the shepherd in a local orbital Frenet frame are:

$$\ddot{\boldsymbol{\rho}} + \left(\boldsymbol{\Omega}\boldsymbol{\Omega} + \dot{\boldsymbol{\Omega}} - \mathbf{G}\right)\boldsymbol{\rho} + 2\boldsymbol{\Omega}\dot{\boldsymbol{\rho}} = \frac{\mathbf{F}_D}{m_D} - \frac{\mathbf{F}_S}{m_S}, \qquad (1)$$

where $\boldsymbol{\Omega}$, $\dot{\boldsymbol{\Omega}}$ represent the angular velocity matrix , $\mathbf{G}$ is the gravity gradient matrix and $\mathbf{F}_D, \mathbf{F}_S$ are the force vectors on the debris (D) and shepherd (S) spacecraft of mass m_D and m_S, respectively.

The above equations need to be accompanied by the shepherd orbit evolution written in inertial axis:

$$\ddot{\mathbf{r}}_S = -\mu \frac{\mathbf{r}_S}{r_S^3} + \frac{\mathbf{F}_S}{m_S}, \qquad (2)$$

where $\mathbf{r}_S$ is the inertial position of the shepherd centre of mass and □ the Earth gravitational parameter.
In addition, the space debris attitude equations of motion in body axes have to be considered:

$$\mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \wedge \left(\mathbf{I}\boldsymbol{\omega}\right) = \mathbf{N}_{tot}, \qquad (3)$$

where $\mathbf{I}$ is the debris inertia matrix (in body axes), $\boldsymbol{\omega}$ the body angular velocity vector and $\mathbf{N}_{tot}$ the resulting gravity gradient and orbital perturbation torques. The equations are written using Euler parameters as state variables and integrated into the IBIS simulator.

Spherical Debris

In order to gain insight into the complex relative dynamics of the IBS-debris system it is convenient to start off with the simplest possible model. To this end we focus on the following scenario:

1. The target debris is modelled as a homogeneous sphere.
2. The initial IBS-debris system orbit is circular.
3. The (axially symmetric) ion beam is constantly pointed along the shepherd instantaneous velocity vector, is kept constant in time, and transmits to the debris a force which only depends on the debris centre of mass location relative to the shepherd. Additional thrusters in the three directions can be used to control the position of the IBS but do not affect the target dynamics (i.e. they are not pointed against the target).
4. External perturbations are limited to the ion beam force and the J2 component of the gravitational potential.
5. The relative position between the debris and the shepherd centre of mass can be estimated at all times with no error and fed to a three-axis thruster-based feedback control system that acts on the shepherd according to a measured position and velocity deviation with respect to the nominal equilibrium configuration.

Figs (3-6) describe the debris-shepherd relative dynamics in Frenet axes, the debris attitude dynamics in body axes and the control effort for the case of a spherical debris of mass 1000 kg and radius 2 m controlled at a relative distance of 10 m from a shepherd satellite of 300 kg mass. An ion beam providing 100 mN nominal thrust with 10 deg initial divergence and Mach number M=30 was considered. For all simulations a 1000-km altitude 82-deg inclination circular orbit was considered.

The debris was given an initial offset of 2 m and 5 m along the radial and tangential direction with respect to the nominal equilibrium position and an initial relative velocity of 5 cm/s and 4 cm/s along the same axes. An optimally-tuned PD controller of the IBS along the R-bar (x axis) V-bar (y-axis) and H-bar (z-axis) direction was employed.

The control strategy is seen to provide relative position stabilisation while the debris angular velocity seems to experience a weak secular increase.

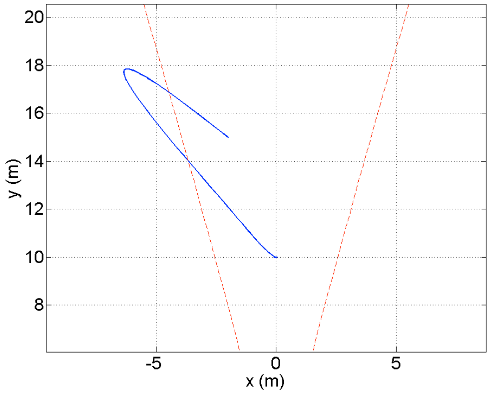


Fig. 3: Debris-shepherd relative trajectory in the x-y plane for the spherical case. The dash line represents the ion beam envelope.

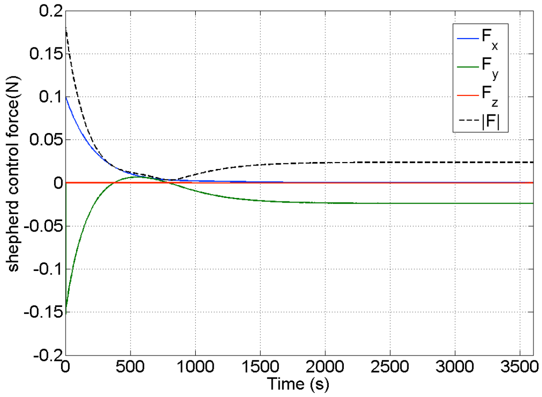


Fig. 4: Shepherd satellite control forces for the spherical debris deorbiting case.

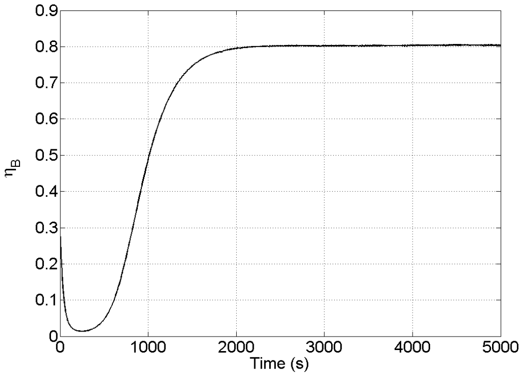


Fig. 5: Spherical debris momentum transfer efficiency variation during the control action.

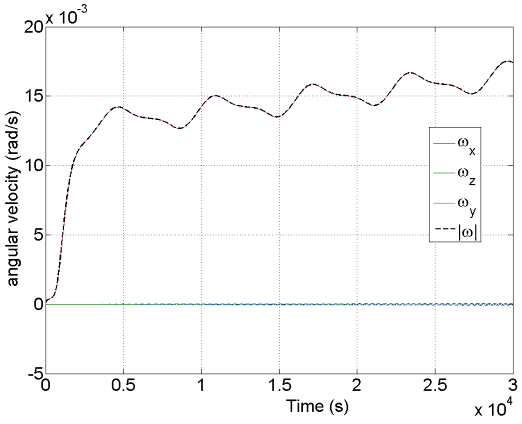


Fig. 6: Spherical debris angular velocity vector components.

Cylindrical Debris

The more complex behaviour of an ion-beam perturbed cylindrical debris has also been analysed and is summarised in Figs. (7-10). An aluminium cylindrical shell of 1500 kg mass, 6.5 m height and 2.4 m radius was considered co-orbiting at 15 m nominal distance from a 300-kg shepherd satellite.

While the axis of the cylinder was initially aligned with the local vertical with zero angular velocity the centre of mass was given an initial velocity of 10cm/s along the radial direction.

The same control strategy utilized for the spherical case is seen to provide good relative position stabilization (Figs. (7-10)). On the other hand the ion beam torque on the cylinder makes it enter a tumbling state whose control will need to be addressed in future studies.

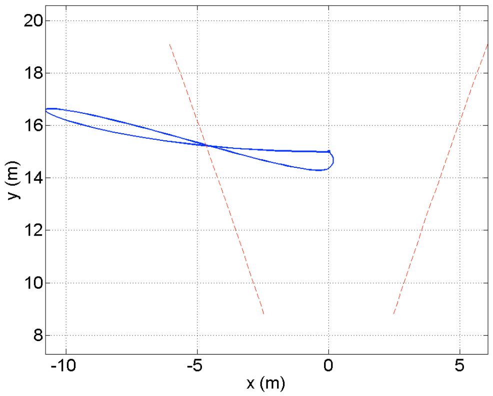


Fig. 7: Debris-shepherd relative trajectory in the x-y plane for the cylindrical case. The dash line represents the ion beam envelope.

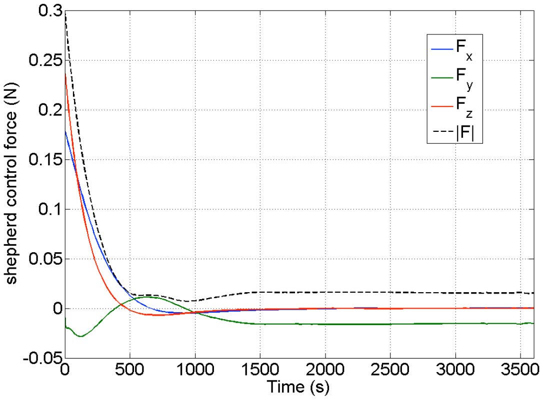


Fig. 8: Shepherd satellite control forces for the cylindrical debris deorbiting case.

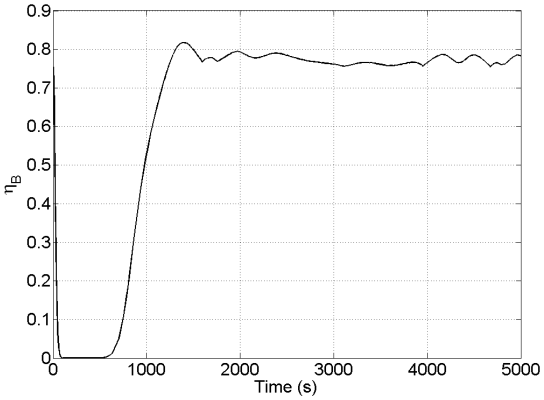


Fig. 9: Cylindrical debris momentum transfer efficiency variation during the control action.

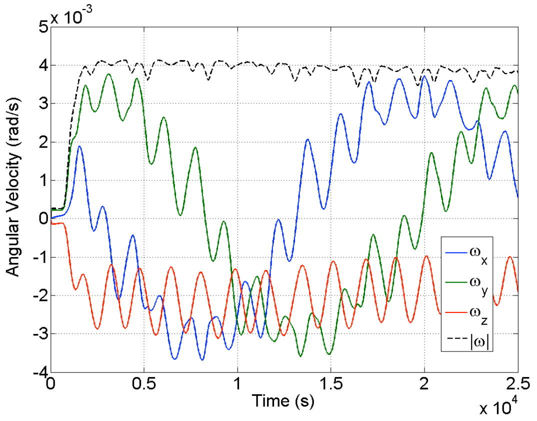


Fig. 10: Cylindrical debris angular velocity vector components.

VI. CONCLUSIONS AND RECOMMENDATIONS

The paper provides a first numerical assessment of the dynamics and control of a space debris co-orbiting with an ion beam shepherd satellites. A three-axis proportional-derivative controller on the shepherd satellite is seen to provide stable relative motion for both spherical and cylindrical debris while the problem of the debris attitude stability and control will need to be dealt with in future studies.

VII. ACKNOWLEDGEMENTS

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