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Input shaped large thrust maneuver with a tethered debris object

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ABSTRACT

In order to reduce the debris population in LEO, remediation is necessary. An active debris removal method is explored that utilizes fuel reserves on a recently launched upper stage to rendezvous with, and tether to, debris. The system's tethered dynamics are explored using a discretized tether model attached to six degree of freedom end bodies. The thrust output is shaped to remove the spectral energy at the natural frequencies of the tether, significantly reducing the post-burn relative motion between the vehicles. The sensitivity of the input shaping performance due to imperfect knowledge of the debris mass demonstrates that a double notch spanning multiple frequencies around the first mode is necessary to be robust to unknown debris mass. On-orbit simulations show that input shaping helps the tethered system achieve smooth oscillations about a gravity gradient alignment, reducing collision likelihood.

1. Introduction

Space debris is becoming a major concern for orbital assets. While there are about 22,000 objects currently tracked, there are many thousands of dangerous debris objects in orbit [1]. In recent years, the creation of debris is on the rise, including two major catastrophic events: the Fengyun 1C anti-satellite test (ASAT) [2] that created over 3300 objects [3] and the Cosmos–Iridium collision [4] that created over 1700 objects [5].

Because of these events and the continued heavy use of low Earth orbit (LEO), the debris cascade effect predicted by Kessler and Cour-Palais [6] is occurring [7]. Mitigation methods have been shown to be important, but offer only partial solutions to reduce the future debris environment. Active Debris Removal (ADR) of five or more large objects per year is shown to be an effective way to reduce the debris population [8]. Some proposed methods [9–14] utilize harpoons, mechanical grapples, or nets to grab the debris object. While the study of the debris capture system is beyond the scope of this paper, all of these methods are likely to use tethers to connect the debris to the ADR craft to avoid close proximity operations between the tug and a tumbling object. While tethers have been studied for years [15] and actually flown on several missions [16], their use in a high force, high thrust environment has been unexplored.

To deorbit debris, the tethers must operate in short-term high stress environments during the large thrust maneuvers ($\sim$2000 N). This paper models the tether dynamics using a series of spring–mass components to discretize the tether into multiple, small masses able to capture higher order modes of the tether (similar models used in [17,18]). The ends of the tether have two, six degree of freedom large rigid bodies: one is the ADR craft and the other is the debris. The ADR craft provides thrust that, transferred through the tether, changes the periapsis of the debris object and reduces both objects' orbital

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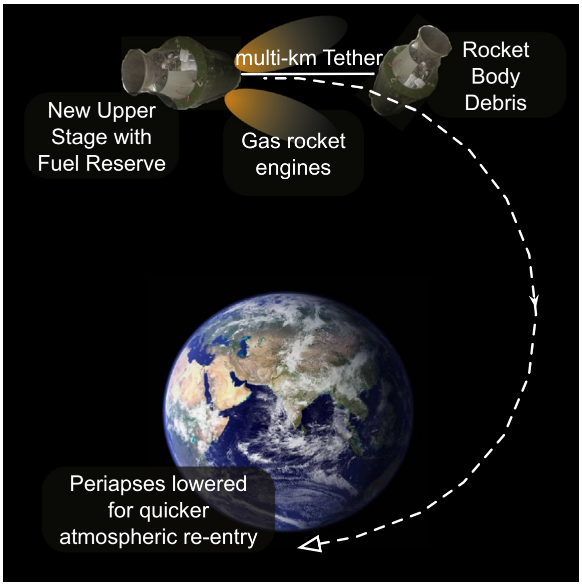

Fig. 1. Tethered tug–debris concept.

lifetimes. Ideally, the ADR craft is a rocket body with remaining fuel reserves that has recently put its payload into orbit. The remaining fuel is used to rendezvous with, and deorbit, the debris. The concept is shown in Fig. 1. Depending upon initial starting altitude and amount of fuel available to the ADR craft, the debris–tug system could be deorbited within a single orbit revolution. The tethered tug–debris architecture therefore provides a cost-effective ADR system because it deorbits two pieces of potential debris each mission.

The challenge when using a tethered tug is avoiding post-burn collision between the debris and tug. The residual post-thrust strain in the tether pulls the two bodies toward each other. Reducing strain and the relative motion between the bodies is necessary to remove collision potential. This paper uses two environments for analysis.

- Deep space: the gravitational field is zero, and the six degree-of-freedom rigid body dynamics problem is reduced to a one-dimensional scenario to analyze the challenges of implementing input-shaped thrusting on a multi-mode, tethered-tug debris system
- On-orbit: the LEO environment is used as well as the full six degree-of-freedom dynamics

In the **deep space** analysis, the mass of the debris object is assumed to not be well known. The effect of this uncertainty on the thrust control and post-burn relative velocity is explored. A deep space environment is a reasonable first order assumption for approximating the dynamics of the tethered system during thrusting because the thrust maneuver only lasts a few minutes. The orbital motion and the deep space motion will not vary significantly during thrusting as low Earth orbits have periods around 2 h.

The deep space environment allows for direct analysis of the tethered-tug system's dynamics. However, to operate in LEO **on-orbit** simulations are required. Of interest is investigating how the post-burn relative velocities impact the motion over a few orbits. The tether is also assumed to be taut in this study because a slack tether results in an undesirable whipping behavior, which will not be explored in this paper. Higher order tether modes, whipping motion and end body rotation are all left to future study. Such studies warrant their own investigation because with the rotational motion of the end bodies, the tether stiffness becomes a function of the tether tension. This greatly complicates the use of input shaping techniques. Rather, the presented analysis uses a lumped mass model to set up the input-shaped maneuver, while the simulations use a higher fidelity model which accounts for the full relative translational and rotational motion.

2. Tether model

The tether is modeled as multiple, discrete point masses. Based upon the tether material and volume the overall mass can be found. This is split into one or more, equally spaced mass particles, commonly referred to as a lumped-mass model [17,18]. Each point mass is connected to its nearest neighbors through a spring. This is shown in Fig. 2. This model allows for flexing of the tether as well as the general motion of the tether due to thrusting forces.

For this paper the tug, debris, tether, and simulation parameters are given in Tables 1 and 2. In Table 1 the mass and inertia values for the Tug are similar to the Soyuz upper stage rocket and the debris values are close to the Cosmos-3 M 2nd stage. Kevlar is used as the tether material because it is commonly used in tether analysis [19] and the diameter of 3 mm is chosen to withstand the stresses experienced. In Table 2 a $\sim$2000 N thrust is chosen to be representative for the Soyuz upper stage thrusters while achieving the worst case, maximum tether tension, as described in Ref. [11]. (Note that the 'step-input' thrust linearly ramps on and off, to and from the max thrust over a period of 1 s.) The Δv capability is based upon the fuel reserves that may be available in the Soyuz after delivering a payload to orbit. Finally, the starting altitude of 800 km is based upon the known high density of Cosmos rocket bodies at that altitude and the fact that they are considered high priority targets for ADR [20].

The values in Tables 1 and 2 are used as a case study for this system, motivated by the original Omsk concept of tugging an upper stage rocket body. Ref. [11] discusses that

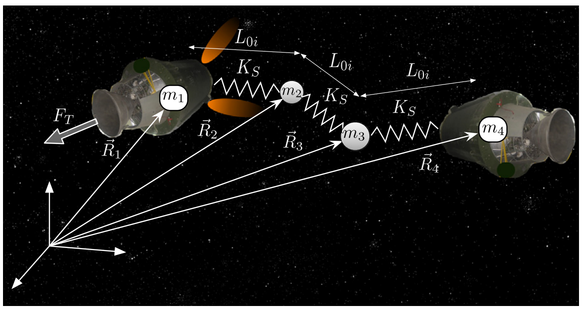

Fig. 2. Tether model: two rigid bodies, two tether point mass.