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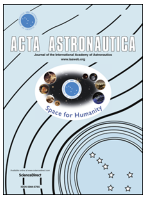

Active debris removal: Aspects of trajectories, communication and illumination during final approach

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ABSTRACT

The aim of this research is to investigate a debris-remediation technique where a chaser performs a rendezvous with the debris, establishes a rigid-link connection, and actively de-orbits the debris. ESA's satellite Envisat has been used as a design case. The research assessed passive safety aspects of the final-approach manoeuvres by analysing the resulting trajectories after thrust inhibit. Next, the research explored the possibility for continuous ground communication by considering the chain of European space tracking (ESTRACK) ground stations (located mainly in Europe). Furthermore, obstruction of the communication signal by the target was studied. Last, the research studies the illumination conditions encountered by the chaser, where obscuration of the Sun by the target was taken into account. Each of these elements are studied for the final approach only. In the topic of passive safety, the results confirm that manoeuvres on H-bar are passively unsafe, and indicate this also for the fly-around manoeuvres along the natural orbital motion. It can be concluded from the communication analysis that the maximum duration of the uninterrupted window varies between 22 and 32 min, using the chain of core ESTRACK ground stations. However, the study on communication blockage shows that frequent communication gaps can occur, with the longest gaps being in the order of one minute in duration. In the field of illumination, it can be concluded that correct target illumination and sensor visibility cannot be guaranteed. Furthermore, the average solar-array area available during final approach varies between 35% and 75%, due to both incorrect pointing of the solar array by the chaser and obscuration by the target.

1. Introduction

Recent studies on the instability of the debris population in low-Earth orbit (LEO) have shown that the environment has reached a point where collisions among existing debris will result in the population to increase, even without any new launches [1]. This scenario is called the Kessler syndrome. Studies show that it is required to remove five large objects per year from highly populated orbits (e.g., LEO) to stabilise the projected growth [2,3]. These studies assume active mitigation measures for new launches on top of the removal of five large objects. However, not all new launches comply with these end-of-life strategies, and because there are still break-ups every year the growth prediction is a dynamic feature. More recent studies show that at least five to ten large objects should be removed per year [4,5]. Because the natural orbital decay of defunct objects alone will not be sufficient, active debris removal (ADR) has to be used.

Such active removal can be achieved in different ways. One way would be to hook up to a (passive) target with a

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Nomenclature

Roman Symbols

$\mathbf{r}$	Position vector (m)
$[x,y,z]$	Position vector components (m)
t	Time (s)
$\mathbf{V}$	Velocity (m/s)
$[\dot{x},\dot{y},\dot{z}]$	Velocity vector components (m/s)

Greek Symbols

α	Azimuth (rad)
γ	Acceleration vector (m/s^2)
$[\gamma_x,\gamma_y,\gamma_z]$	Acceleration vector components (m/s^2)
Δx	Change of quantity x (-)
ϵ	Spacecraft elevation angle (rad)
θ	Elevation (rad)
ω	Mean motion (rad/s)

tether by harpoon or net [6], and either passively (with an electrodynamic tether that induces a Lorenz force by interacting with the Earth's magnetic field [7]) or actively (by pulling with a dedicated propulsion unit or actual spacecraft [8,9]) remove the target from orbit such that it will enter the atmosphere. Another option could be that of a rendezvous of an active chaser spacecraft with the target, dock to it, and use the chaser's propulsion system to force the combination to deorbit and move towards the atmosphere.

An ADR study, named e.deorbit, has been carried out at the European Space Agency (ESA) to investigate the possibility for an ADR mission using a chase and catch approach. The e.deorbit mission aims at removing a single, large, non-operational satellite from LEO and is intended for launch in 2021 [10]. In that research a rigid-link connection has been considered between the chaser and the target. Such a mission faces major challenges in the rendezvous, capture and de-orbit phase of the mission.

The rendezvous mission is typically divided into a number of main phases. After launch and injection of the chaser into the orbital plane of the target, the orbit phase angle will be reduced to bring the chaser roughly in the vicinity of the target. With relative navigation, the far-range rendezvous guidance will transfer the chaser from the phasing orbit to a first aim point in close vicinity of the target. The close-range rendezvous consists of two sub-phases, notably the final approach to the capture point and the closing phase to acquire the final-approach line. Finally, the actual docking takes place by establishing a structural connection. The main focus of this paper will be on the final-approach phase up to, but not including, the docking to the target.

Fehse [11] describes a number of challenges for an ADR mission, among others absolute and relative navigation including the required sensors during the rendezvous, as well as the capture process and structural connection between chaser and target. The main challenge comes from the fact that the target is uncooperative. The rendezvous with uncooperative objects requires flexible guidance strategies to cope with variable target motions. To avoid a catastrophic collision between the chaser and the target, passive safety measures must be incorporated in the trajectory design. Proper communication and illumination conditions, or rather lack thereof, only contribute to the complications.

Communication conditions for a non-cooperative rendezvous mission in LEO are expected to be very demanding for orbit control. To begin with, the communication windows in LEO are relatively short. Per ground station a communication window of roughly 10 min may be expected. The lack of communication with the chaser during the final approach would require high on-board autonomy of the chaser, which is undesired in a novel mission that implements many immature technologies. Therefore, it would be beneficial to have continuous contact with the spacecraft during the final approach, such that the rendezvous can be humanly supervised. This can be envisaged by using a chain of ground stations. For rigid-link connections, the distances between the chaser and target will be small during the final approach to allow for capturing the target. As a result, the communication signal may be obstructed from reaching the ground stations.

The illumination conditions in LEO can be quite challenging for rendezvous, not only for navigation sensors that require visible light, but also for power supply of the chaser. Due to the short orbital period (90–100 min), the Sun direction changes quickly in time. Also, a large part of the orbit is eclipsed (except for orbits near the dawn–dusk region). The navigation system must be able to cope with these conditions. The small distance required between the chaser and target during the final approach also impacts the energy that can be produced by the solar array, because it cannot be guaranteed that the solar array is able to receive Sunlight, as it may be obscured from the Sun by the target. At the same time, the power requirements during the final approach may become high due to the use of a robotic arm, navigation sensors and artificial lighting.

This research addresses the challenges identified above, which can be classed in three categories: final approach, communication and illumination. The structure of this paper is as follows. First, in Section 2 the models and definitions adopted in the research are summarised. Section 3 describes the methodology of the research. The results of the research are presented in Sections 4, 5, and 6, respectively. Section 4 deals with the final approach, Section 5 with communication, and Section 6 with illumination. Finally, Section 7 summarises the conclusions of the research.

2. Definitions and models

The research has been performed in the framework of ESA's e.deorbit feasibility study and therefore the