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Pose estimation and tracking of non-cooperative rocket bodies using Time-of-Flight cameras

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ABSTRACT

This paper presents a methodology for estimating the position and orientation of a rocket body in orbit – the target – undergoing a roto-translational motion, with respect to a chaser spacecraft, whose task is to match the target dynamics for a safe rendezvous. During the rendezvous maneuver the chaser employs a Time-of-Flight camera that acquires a point cloud of 3D coordinates mapping the sensed target surface. Once the system identifies the target, it initializes the chaser-to-target relative position and orientation. After initialization, a tracking procedure enables the system to sense the evolution of the target's pose between frames. The proposed algorithm is evaluated using simulated point clouds, generated with a CAD model of the Cosmos-3M upper stage and the PMD CamCube 3.0 camera specifications.

1. Introduction

During the last decade, several studies have analyzed the feasibility and performance of autonomous agents executing On-Orbit Servicing (OOS) tasks see e.g. Ref. [1]. Successful implementations of this concept may significantly extend the lifetime of a satellite and facilitate in-orbit tasks such as debris removal. One of the issues to be tackled is the rendezvous between an orbiting object (hereafter referred to as the target) and a chaser spacecraft. Previous missions have demonstrated the feasibility of autonomous rendezvous between two cooperative spacecrafts, e.g. ETS-VII, XSS-11, DART and Orbital Express [2]. In these missions, either the target provided its own position and attitude to the chaser, or ad-hoc visual markers on the target's surface enabled the chaser to autonomously obtain the relative pose [3].

More demanding scenarios involve non-cooperative targets, such as Active Debris Removal (ADR) missions [4]. The main objective of ADR is the safe capture and proper disposal of space junk, either by forcing the debris to reenter the atmosphere or by placing it on a graveyard orbit. Examples of non-cooperative targets are inoperative satellites, payloads, or rocket bodies. Due to size, impact probability, and ignition risks as a result of unused fuel, the latter are given higher priority for potential ADR missions. In this work, we specifically focused on the upper stage of the Russian launcher Cosmos-3M, identified as SL-8 in the space surveillance catalogs [5].

The chaser's main task during the final approach is the autonomous identification of the target's geometrical properties and kinematics that enable it to safely perform the adequate encounter maneuvers. Due to the non-cooperative nature of this scenario, the chaser has to remotely sense the target. This is achieved by employing different sensors, in order to estimate either the line-of-sight (LOS) and/or range to the object, or the full 6 degrees-of-freedom (DOF) pose of the target. Passive cameras can provide 6DOF pose estimation through model matching [6] or binocular stereo vision [7], or output LOS vectors pointing to the target [8]. Thermal imaging can also be used for estimating both LOS and range to target [9]. Active sensors, such as radar, lidar or active cameras, are a viable alternative for sensing the target surface. A radar was used on the Space Shuttle in both cooperative and non-cooperative missions for calculating range and LOS [2], whereas lidar has been widely employed for full 6DOF pose estimation [10–12]. Active cameras may represent the best sensing solution in many applications, since these combine the advantages of visual- and range-based systems. Active cameras allow for a reconstruction of the target's surface with matching metric, independently from the surface's texture required by a stereoscopic setup [7] and without the scale ambiguity that characterizes monocular systems [13].

Multiple ADR solutions have been recently proposed, aiming at reducing the dangers associated to the safe capture of free-floating orbital structures. Many solutions are model-based [14,15], or employ point cloud global descriptors [16–18] for target pose initialization. In both cases, the need of a training database built in a previous off-line phase may introduce a dependency on both the number of simulated poses, and

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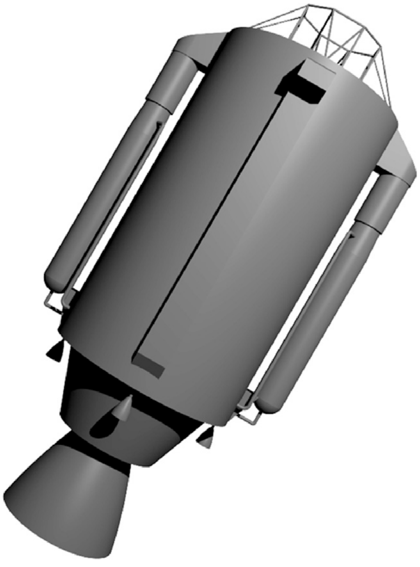

Fig. 1. 3D CAD model of the Cosmos-3M upper stage.

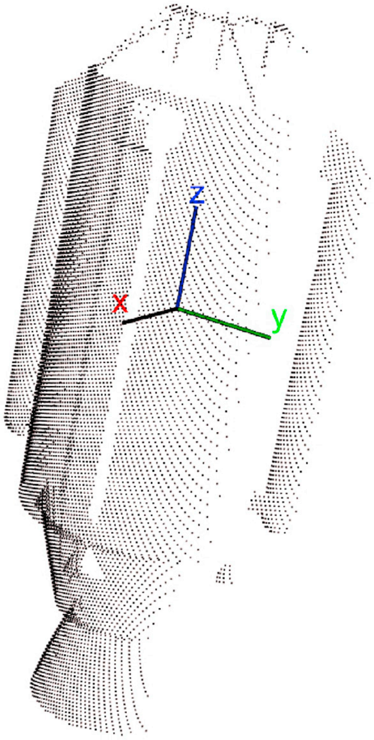

Fig. 2. Simulated point cloud from the Cosmos-3M rocket body. The body reference frame is defined as follows: the *X*-axis points towards the frontal fairing, the *Y*-axis towards the lateral tank, and the *Z*-axis is aligned with the main cylinder's longitudinal axis.

the performance of the model/descriptor matching procedure. Other works have analyzed the pose estimation problem using photonic mixing device (PMD) cameras [19,20], focusing on satellites whose structure is mainly composed by planar surfaces. A recent work has included a simplified version of a rocket body shape [15], in which the target tracking loop is based on a trained model.

This work analyzes the performance of a chasing routine that employs an active Time-of-Flight (ToF) camera to determine the kinematics of a free-floating rocket. The routine identifies the object to be approached, extracts the target orientation, and estimates the target kinematics. Thus, continuous information about the position and orientation of the target is provided to the chaser control system. Among diverse methods proposed for capturing an orbiting object [21], here we assume a chaser platform equipped with a robotic arm [22]. The capturing maneuver must be executed when the kinematics of the target are matched by the chaser to avoid potentially disastrous events, such as the partial or total loss of control of the chaser satellite and/or its arm, and the production of additional debris due to impacts.

The outline of the paper is as follows: Section 2 introduces the point cloud technique used to sense the target, as well as the method implemented to retrieve the sensed body geometrical information; Section 3 deals with the target relative pose initialization; Sections 4 and 5 describe the object tracking routines; Section 6 the simulations and relative results to test the methods presented in previous sections are discussed. The conclusions are drawn in Section 7.

2. Point clouds

The active 3D imaging method used for this work is based on the time-of-flight principle [23]: infrared light modulated by a signal of lower frequency (typically a few tens Mhz) is emitted, and a portion of the reflected light is captured by a receiver sensor that records both brightness and emitted-to-received phase shift. The latter is proportional to the range ρ between the sensor and the observed object:

$$\rho = \frac{\lambda \Delta\phi}{4\pi}, \tag{1}$$

with λ and $\Delta\phi$ being the modulated signal wavelength and recorded frequency shift, respectively. The ToF camera outputs three information layers: a brightness matrix, an amplitude matrix (proportional to the received signal strength), and a depth map [24]. Combining these layers with a-priori knowledge of the camera's intrinsics (i.e. focal length, pixel skew coefficient and optical center) enables the user to obtain a set of distributed points in the 3D euclidean space, with coordinates given in the sensor reference frame. This set is known as point cloud, and represents the observed surface of an object that allows retrieving several characteristics of the objects in quasi-real time, among which its size and surface geometry.

2.1. *Retrieval of geometrical information*

The first task to be executed by the system is the recognition of the target's geometrical properties. We assume that a-priori information about the target is available: focusing on chasing a rocket body, we assume an expected cylindrical body shape of known radius, with a number of appendices (fairings, side-tanks) and a nozzle on one of the two extremities. Such information can be extracted from a computerized model of the rocket body, if available, or from public data. It is important to stress that only the characteristics of very descriptive structures are required, such as the nozzle, the fairings' location and shape, and the form and size of any appendage attached to the main body. Fig. 1 shows the 3D CAD model of the Cosmos-3M upper stage, and Fig. 2 is a simulated point cloud based on such a model, where the body reference frame is visualized.

2.1.1. *Identification of the cylindrical axis*

The initial information to be retrieved is the axis of symmetry of the main cylindrical body. This is accomplished by first dividing the sensed surface in sub-patches, i.e., sub-sets of the point cloud containing a limited number of points. The size of the sub-patches is determined so to include a minimum number of points surrounding the “query point” within a fixed distance. A query point is any element in the cloud that will be subject of any operation that takes into account the surrounding points. Thus, the patches size depends on the density of the point cloud (i.e. the distance between the target and the sensor) as well as on the level of detail required by the application addressed: the more query points are