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Image-based attitude maneuvers for space debris tracking

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ABSTRACT

This paper proposes an image-based control scheme for tracking space debris using onboard optical sensors. The proposed strategy uses an onboard camera for detecting space debris. The camera is rigidly attached to the satellite; therefore specific attitude maneuvers need to be performed during different phases of the mission. First, the spacecraft orients its attitude to point the camera toward a fixed direction in space, and then when debris traces streak across the field of view of the camera, the spacecraft follows and tracks the motion of the debris. Finally, a disengagement maneuver is executed to stop the spacecraft rotation when the debris disappears from the camera field of view. The model and the developed control scheme take into account the typical characteristics of space-qualified cameras, and a Kalman filter is developed to reduce the effects of the camera noise, detect and predict the path of the debris in the image plane, and estimate the angular velocity of the spacecraft. The entire estimation/control scheme is then validated through numerical simulations, using a model of reaction wheels as the main attitude actuation system. The results demonstrate the viability of such maneuvers in a typical space debris surveillance mission scenario.

1. Introduction

SPACE debris is becoming the issue of main concern amongst the space community because of its repercussions on the present and future space missions. Indeed, uncontrolled objects produced by past space missions are sources of possible collisions with operative and non-operative satellites [1]. Despite the recent establishment of some mitigation guidelines [2], more collisions such as the Iridium 33–Cosmos 2251 incident in 2009 are probable, and they can cause a cascade of crashes that may compromise the future utilization of space [3]. Such catastrophic scenarios were hypothesized in 1978 as Kessler syndrome [4]. Even without any new launches for at least the next 200 years, some recent studies have shown that we may have already reached the non-equilibrium point in a sense that, given the probability of the future collisions between the existing objects, the LEO population will continue increasing [5,6]. Therefore, constant monitoring of the space debris trajectories has been recognized as a necessary regular practice for identifying potential threats and timely planning of collision avoidance maneuvers. As an example, such maneuvers have been planned in the past for rescuing the International Space Station from collisions with space debris if the probability of collision was greater than 10^{-5} [7].

Generally speaking, debris avoidance maneuvers may be planned from one to several hours ahead of the conjunction, as long as the threatening debris can be detected and identified in time. Therefore, it is required to have a prompt network of observation facilities devoted to the space debris surveillance, assuring high levels of precision and readiness. Agencies, such as USAF and ESA, have developed their networks of Space Situational Awareness (SSA), utilizing mainly ground-based radars and telescopes [8,9].

Onboard sensors have been introduced first as auxiliary tools for improving the space debris observations [10–12], but then they turned as fundamental assets for current and future SSA programs [13,14]. Indeed, onboard observations offer greater performances in terms of accuracy, large field of view and weather independency. Further, space-borne measurements are not interrupted by the daylight, and they are not characterized by the scattering, diffractions, aberrations and turbulences in the atmosphere [15]. Though the exploitation of the radar technology has been proposed for overcoming limitations due to light conditions of optical sensors and increasing the number of detections of small-sized debris, its onboard implementation requires considerable expenditure, in terms of power consumption and spacecraft size and mass [16–18]. Thus, the utilization of optical sensors, such as CCD [19], CMOS

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[20] or photon counting sensors [21], appears to be a cost-effective and viable solution for such missions, also thanks to the recent improvement of their accuracy [8].

The recent advances in the miniaturization of space components, increasing processing capabilities of onboard computers, as well as the state-of-the-art optical sensors seem to have become sufficiently mature for proposing new space mission concepts that involve small satellites, such as Cubesat platforms. This is the case for mission concepts such as the Autonomous Assembly of Reconfigurable Space Telescope (AAReST) mission [22], the Space-based Telescope for Actionable Refinement of Ephemeris (STARE) mission [23], or the Sapphire mission [12].

Following this trend, a new mission for space debris surveillance has been proposed in [24], where a network of distributed optical sensors is utilized in a formation of multiple spacecraft. The premise of such proposal is that multiple satellites can coordinate themselves for detecting and tracking common targets by using the concept of multiple point of view observations. That is, two or more spacecraft can re-orient their optical sensors toward a common object, and estimate the position of debris by sharing the measured data. As a result, teams of multiple satellites can be formed *ad hoc*, and autonomously detect and track unknown debris, estimate their trajectories, and send the results of the estimations directly to the mission control centers for planning the required collision avoidance maneuvers. Specifically, the viability of the mission concept and the algorithm for debris orbit estimation has been discussed in [24], where it has also been shown the necessity of having at least two observing satellites for the correct estimation and convergence of the Kalman filters. Then, an attitude coordination algorithm amongst the satellites has been developed and analyzed in [25], allowing for a correct pointing of the onboard sensors through attitude maneuvers, once the debris is detected and tracked by one of the satellites. Finally, an integrated attitude/estimation coordination algorithm has been developed in [26], which allows for autonomously grouping those satellites that can share data and perform the required attitude maneuvers.

This paper completes the mission concept for multi-satellite space debris surveillance by proposing a solution to one remaining crucial problem. Specifically, the previous developments assumed that the satellites were able to detect and track debris with their optical sensors. The present paper investigates more in detail the algorithms for debris recognition from image frames taken by the onboard cameras and how the satellites can track debris by using a vision-based controller. An algorithm for space-based optical tracking of space objects is presented in [27], where quaternion-feedback control laws are designed to align the camera principal axes to the line of sight between the observing satellite and the observed object. The approach presented in this paper uses control laws defined directly in the image domain, by extracting visual features of stars and moving objects in the camera field of view. Further, the resulting nonlinear controller is based on the application of the Lyapunov direct stability criterion and presents feed-forward terms that are estimated through a Kalman filter. The implementation of the Kalman filter allows for an estimation of the angular rate of the spacecraft and of the relative velocity of the debris in the image plane of the camera by using camera and gyroscope measurements.

A model of the satellite is described in Section 2, including the onboard camera. The visual features extracted from the images of the onboard camera are then used as an input to the nonlinear, Lyapunov-based controller developed in Section 3. Further, four operative modes are defined in the section for performing the tasks required for the space surveillance mission. The effects of noise on the controller and its reduction through Kalman filtering techniques are described in Section 4. The numerical results are discussed in Section 5, verifying the viability of the developed estimation and control mechanisms. Section 6 summarizes the main outcomes of this study.

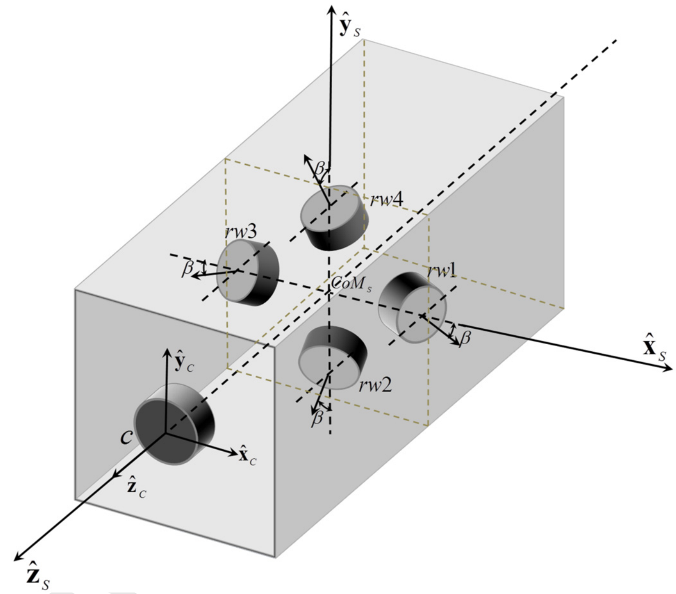

Fig. 1. Satellite platform with the attitude control and camera subsystems and their associated reference frames.

2. System modeling

A model of the satellite platform, with the attitude control and vision subsystems and their relative coordinate frames, is presented in Fig. 1. The origin of the satellite coordinate frame, denoted as $\{S\}$, is at the center of mass (CoM), and the onboard camera (C) is attached to one side of the satellite body. The attitude control is actuated by four reaction wheels, denoted as *rw1*, *rw2*, *rw3* and *rw4*, placed in a pyramidal configuration so that their rotation axes are inclined with respect to the $\mathbf{x}_S\mathbf{y}_S$ plane by angle β. This configuration guarantees 3-axis stabilization as well as reliability against the failures of one of the wheels [28]. The camera coordinate frame $\{C\}$ is attached to the satellite, with its axes parallel to those of $\{S\}$. Thus, the image plane $\mathbf{x}_C\mathbf{y}_C$ is parallel to the $\mathbf{x}_S\mathbf{y}_S$ satellite body plane, and the camera optical axis $\mathbf{z}_C$ is aligned with the satellite $\mathbf{z}_S$ axis. In the following, the description of both the attitude dynamics and camera models are presented for providing some fundamental definitions and concepts that will be used for developing the vision-based control scheme.

2.1. Attitude dynamics model

The equations for describing the attitude of the satellite are obtained using the conservation of the angular momenta, as follows:

$$ {}^{S}\dot{\mathbf{h}}_S = {}^{S}\mathbf{T}_E - {}^{S}\tilde{\boldsymbol{\omega}}_S\,{}^{S}\mathbf{h}_S \tag{1} $$

where $\boldsymbol{\omega}_S$ is the angular velocity of the platform, and $\mathbf{T}_E$ is the external torque applied to the system, $\mathbf{h}_S$ is the total angular momentum of the satellite which can be divided in two components: the angular momentum of the satellite bus $(\mathbf{h}_B)$ and the angular momentum due to the motion of reaction wheels $(\mathbf{h}_W)$. The pre-superscript S indicates that the above-mentioned vectors are defined in the $\{S\}$ coordinate frame, and the $\sim$ symbol represents the 3×3 skew-symmetric matrix built from a vector components. Assuming that the satellite bus can be modeled as a rigid body $(\mathbf{h}_B = \mathbf{I}_B\boldsymbol{\omega}_S)$ and considering that the control torque applied to the

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