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Attitude recovery from feature tracking for estimating angular rate of non-cooperative spacecraft

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ABSTRACT

This paper presents a fault-tolerant method for estimating the angular rate of uncontrolled bodies in space, such as failed spacecraft. The bodies are assumed to be free of any sensors; however, a planned mission is assumed to track several features of the object by means of stereo-vision sensors. Tracking bodies in the space environment using these sensors is not, in general, an easy task: obtainable information regarding the attitude of the body is often corrupted or partial. The developed method exploits this partial information to completely recover the attitude of the body using a basis pursuit approach. An unscented Kalman filter can then be used to estimate the angular rate of the body.

1. Introduction

The estimation of attitude and angular rate of artificial satellites is a very well-known process that is normally performed using the appropriate on-board instrumentation. Very common associated techniques are sensor fusion and Kalman filtering; data captured by star trackers and gyros are combined with dynamic models of the system to produce an on-orbit estimate of the state, which includes the inertia tensor, which changes over time because of fuel consumption [1]. This information is required for stability control of the active spacecraft. Several studies have been performed to relieve some of the used sensors to prevent failures and to reduce costs, particularly for missions involving small spacecrafts [2]. Additionally, gyro-less control systems that use only star tracker information as the input of accurate non-linear Kalman filters have been developed.

The estimation problem becomes difficult when artificial objects have no active sensors at all, i.e., in the case of failed spacecrafts. No direct information regarding the attitude of the object might be available and obtaining this information by exploiting external sensors (e.g., CCD cameras on a chaser spacecraft) is, in general, a difficult task.

Space debris removal is becoming an urgent environmental issue related to space exploration. As assessed by the U.S. Space Surveillance System, the number of objects that orbit the Earth has increased significantly over the years [3]; the risks of collisions between active and lost spacecrafts may soon become consistent. Additionally, no docking or de-orbiting maneuver can be considered safe without precise knowledge of the attitude and angular rate of the target debris. Lichter and Dubowsky [4] proposed an architecture for the estimation of the dynamic state of non-cooperative spacecrafts. This architecture primarily consists of 3D active sensors, which are suitable for use in harsh lighting conditions. Aghili et al. [5]

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presented a method for pose estimation of passive space bodies using a laser 3D scanner. Their method also considers the possibility of failures during the scanning procedure without compromising the estimation. However, this method requires a CAD model of the object.

The use of active sensors, although they are relatively reliable, could nevertheless be less appealing than obtaining the same information using stereo-vision sensors, because of the possibility of saving energy and costs. A survey of the most common tracking techniques based on stereo-vision can be found in [6]. In [7] and [8] two different methods are presented to maintain a target space body in the field of view (FOV) of cameras on a chaser spacecraft after the rendezvous phase. In these studies, estimation of the angular rate is not performed. Both of the methods seem to be applicable over a relatively long time period. The main drawback of methods that exploit stereo-vision cameras is that different phenomena (such as occlusions or disturbing reflections) cause discontinuous tracking of the natural features of space objects. In spite of this, recently, several authors have attempted to prove the effectiveness of these systems.

In [9] a 3D-model-matching technique, as used in [5], is combined with stereo-vision sensors. The considered method requires a large number of detected features and a very detailed model of the failed satellite. In [10], a powerful method based on stereo vision to track a non-cooperative spacecraft and to estimate its complete dynamic state is presented. The method does not require any *a priori* information about the target; however, it is assumed that the positions of at least three features are always measurable. For that reason, although the method has shown very good accuracy, it would be not applicable if occlusions occur during tracking or if in some instant of time the detectable features are less than three.

In [11], the tracking of a target body relative to a chaser is achieved via the prediction of the velocities of its features. This prediction is based on a kinematic model of the object. In this work, the problem of recovering the pose and the angular rate of the object during occlusions is considered; however, no results are shown in the case in which no features are detectable. Moreover, when the number of detected features decreases, the precision of the estimation significantly decreases. The paper states, however, that the prediction is useful for re-initializing the tracking.

The work presented in [12] considers the determination of the relative pose between a chaser and a larger target that are cooperative. This work is interesting for two reasons: tracking is performed using stereo-vision cameras and when occlusions occur, although the attitude information is lost, the position of the body is predicted using a mathematical model of the body itself. The tracking can then continue after the occlusion periods; however, the pose of the object is not obtained in these periods. An important assumption underlying the cooperativeness between the spacecrafts is that the positions of certain artificial features on the target (in the case considered, LEDs) are known *a priori*.

Definitely, the current state of the art appears to be missing of fault-tolerant methods for attitude estimation from features detected by means of stereo cameras. The method proposed in this paper offers the possibility of recovering attitude information of a space body such as a failed spacecraft, even if the continuity of the feature tracking is missing. Thus, the method is applicable to recover the object pose also if momentary failures in feature detection occur. The method can also be applied in conditions similar to those in [12].

The fundamental assumption that allows the presented algorithm to succeed is the ability to track several features (i.e., corners, edges, tips, or other recognizable parts) of the object using two cameras on a controlled chaser spacecraft. Measurements must be available at least for frequent and short intervals of time. Data samples should consist, in particular, of the Euclidean coordinates of the features with respect to a reference frame with the origin in the center of mass of the chaser. This hypothesis seems to be reasonable considering the previously mentioned state of the art.

Another assumption concerns knowledge of the relative positions between the detected features. This knowledge can be achieved during tracking: if a 3D model of the object is available, it is possible to associate the few detected features with the corresponding points on the model. It is not necessary that the model be highly detailed, as only a small number of features need be recognized. For example, in [13], sequential photographs of a passive space body provide knowledge of the pose of the camera with respect to a 3D model of the object. This method allows recognition of the correspondences between detected features and specific points on the model. If no model is available, the relative positions could be estimated by averaging many measurements and by constraining the distances between detected features to be constant. This last method is difficult to achieve because it would require that the tracking architecture be capable of associating each feature with a unique label and recognizing it when it is detected.

The principle underlying the procedure is as follows: once a corrupted attitude signal is generated from the input data, it is possible to recover the signal by converting this operation into a non-linear optimization problem under the assumption that the original signal can be treated as the composition of a small number of elementary signals. This approach is common in signal processing, especially in fields such as image recovery, signal decoding, and signal deconvolution. This approach has also been successfully used for solving prognostic problems related to mechanical systems such as gear boxes [14,15]. However, this technique has seldom been applied to the estimation of kinematic quantities from raw data. Additionally, it uses one of the most effective existing approaches [16], i.e., the basis pursuit approach. This method is quite adaptable to situations in which signals are affected by noise (*basis pursuit denoising*); it has been proven, through numerical simulations, to be very effective in the recovery of attitude signals. The optimization problem is solved using a fast and reliable algorithm, SALSA [17], an acronym of split augmented Lagrangian shrinkage algorithm.

Once the attitude is available, the angular rate can then be estimated via classical methods based on Kalman filtering, because of the strict correlation between angular rate and attitude. However, this last aspect is not the main purpose of the paper; the main intent consists instead in proposing a novel method for recovering the attitude from features also in the case of temporary losses of measured data.