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Stereovision-based pose and inertia estimation of unknown and uncooperative space objects

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Abstract

Autonomous close proximity operations are an arduous and attractive problem in space mission design. In particular, the estimation of pose, motion and inertia properties of an uncooperative object is a challenging task because of the lack of available a priori information. This paper develops a novel method to estimate the relative position, velocity, angular velocity, attitude and the ratios of the components of the inertia matrix of an uncooperative space object using only stereo-vision measurements. The classical Extended Kalman Filter (EKF) and an Iterated Extended Kalman Filter (IEKF) are used and compared for the estimation procedure. In addition, in order to compute the inertia properties, the ratios of the inertia components are added to the state and a pseudo-measurement equation is considered in the observation model. The relative simplicity of the proposed algorithm could be suitable for an online implementation for real applications. The developed algorithm is validated by numerical simulations in MATLAB using different initial conditions and uncertainty levels. The goal of the simulations is to verify the accuracy and robustness of the proposed estimation algorithm. The obtained results show satisfactory convergence of estimation errors for all the considered quantities. The obtained results, in several simulations, shows some improvements with respect to similar works, which deal with the same problem, present in literature. In addition, a video processing procedure is presented to reconstruct the geometrical properties of a body using cameras. This inertia reconstruction algorithm has been experimentally validated at the ADAMUS (ADvanced Autonomous MUltiple Spacecraft) Lab at the University of Florida. In the future, this different method could be integrated to the inertia ratios estimator to have a complete tool for mass properties recognition.

Keywords: Pose and inertia estimation; Stereo-vision; Autonomous close proximity operations; Resident space object; Video processing

1. Introduction

Over the past few decades, spacecraft autonomy has become a very important aspect in space mission design. In this paper, autonomous spacecraft proximity operations are discussed with particular attention to the estimation of position and orientation (pose), motion and inertia properties of an uncooperative object. The precise pose and motion estimation of an unknown object, such as a Resident Space Object (RSO) or an asteroid has many potential applications. In fact, it allows autonomous inspection, monitoring and docking. However, dealing with an uncooperative space body is a challenging problem because of the lack of available information about the motion and the structure of the target. The interest of the main space agencies, in these years, is focused on the gradual automation of the space missions because of its large number of practical applications. In this way, the high risks and costs deriving from the presence of humans on-board can be

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significantly reduced. For example, in 2005, NASA sponsored the DART (Demonstration for Autonomous Rendezvous Technology) (Clohessy, 2006) project to develop and demonstrate automated navigation and rendezvous for a spacecraft. DARPA, in 2007, launched the Orbital Express mission (Friend, 2008) aimed at developing an approach for autonomous satellites servicing in orbit. Moreover, relative navigation between non-cooperative satellites can become a powerful tool in missions involving objects that cannot provide effective cooperative information, such as faulty or disabled satellite, space debris, hostile spacecraft and asteroids. In particular, the precise pose and motion estimation of an uncooperative object has possible applications in the space debris removal field. Space debris includes all man-made defunct objects, in Earth orbit or re-entering the atmosphere. The pose and the inertia matrix estimation is the first step to implement a system to recover and remove elements harmful to operational and active satellites. Additionally, the obtained algorithm can be installed on autonomous spacecraft for close-proximity operations to asteroids or for rendezvous manoeuvres. In this regard, for the near future, ESA is developing a mission for space debris removal, e.DeOrbit (Biesbroek et al., 2013) that plans to capture derelict satellites adrift in orbit. No matter what technology will be used, the estimation of the relative state will be a main technical challenge. This step will be necessary for assessing the condition of a drifting object, left in an uncertain state, and to approach it. Furthermore, the mission AIDA (Galvez et al., 2013), planned for the 2022, will be the first mission to demonstrate asteroid impact hazard mitigation by using a kinetic impactor to deflect an asteroid. To do this, an Asteroid rendezvous spacecraft is needed and it has to precisely and autonomously estimate the relative state of the asteroid, before and after the impact. Moreover, implementing autonomous robotic systems able to perform autonomous inspection, docking, on-orbit servicing and refueling, would represent a big step in the space operations field. All these operations are nowadays performed by manned systems and the main agencies are trying to automatize these processes. For this reason, this paper wants to present algorithms enabling the knowledge of the relative state, in particular, it focuses on the problem of how to estimate the relative state and the inertia matrix of an unknown, uncooperative space object using only stereoscopic measurements. This information is provided by two cameras. The methodology developed to solve this problem has many potential applications in other fields (iceberg-relative navigation (Kimball, 2011), biomedical applications (Grasa et al., 2011), vision-based unmanned aerial vehicle navigation (Bryson and Sukkarieh, 2007), etc.). Current literature addresses the problem of relative state estimation with respect to an uncooperative object, assuming partial knowledge of the geometry or feature points of the target (Philip and Ananthasayanam, 2003). In other cases, multiple spacecraft or sensors with high power consumption (3D-sensors Lichter et al., 2004, 2005 or LIDAR Shahid and Okouneva, 2007; Fenton, 2008) are utilized to compensate for the lack of information. The algorithms exploiting LIDAR have also the disadvantage of being computationally expensive. In this sense, some recent works try to reduce the computational cost of this kind of techniques (Opromolla et al., 2015b; Liu et al., 2016). None of these proposed algorithms has been physically implemented in a real application, one main reason being their high computational cost. One of the main contribution in literature, addressing relative state estimation of an uncooperative target is from Lichter (Lichter et al., 2004, 2005). He solves the problem of estimating the relative pose, motion and structure using a 3D vision sensor. This creates and processes point clouds to reconstruct the geometric shape of the object. From this information, he is able to extract a rough measurement of the centroid and rotation matrix. Then, two Kalman Filters (translation and rotation) are used to estimate the state and inertia properties. However, using 3D sensor involves more power consumption, computational cost and data to manage. In 2013, Segal and Gurfil presented a solution of the state estimation of a non-cooperative spacecraft using an Iterated Extended Kalman Filter (IEKF) (Segal et al., 2011, 2014). Their approach was the baseline for this research. They develop and utilize a translational-rotational coupled model to describe the relative dynamics. Then, an IEKF is used to estimate the state. The basic assumption is to have only stereoscopic measurements. However, they do not estimate the inertia matrix, but they run N Kalman filters in parallel and, at the end, they choose the best value for the inertia tensor according to a Maximum A Posteriori (MAP) estimation. Thus, N filters must work simultaneously for an interval of time t to estimate the state. Then, all the estimated states are compared and the selected inertia matrix is the one that provides better results in terms of state error. This method clearly cannot be implemented on a real spacecraft because of the large computational cost needed in problems without previous knowledge of geometry information. Another method for the estimation of the inertia matrix was proposed in Benninghoff and Boge (2015). They solve a constrained least squares problem for the estimation of the center of mass and inertia properties. However, they do not model the observations, assuming to know all the dynamical quantities with noise. For this reason, the analyzed scenario is not very realistic. A very interesting work was published by Tweddle and Saenz-Otero (2014) and Tweddle (2013). Assuming a stationary leader, he developed a method to estimate the state and structure of an unknown object using a smoothing algorithm. Smoothing and Mapping (SAM) are commonly used for simultaneous localization and mapping (SLAM) problems. This method estimates the complete 'robot' trajectory in time and not only the current pose. The particular smoothing algorithm used by Tweddle is the Incremental Smoothing Algorithm (iSAM) introduced by Kaess et al. (2008, 2007). This method performs fast incremental updates to compute a