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# Relative dynamics estimation of non-cooperative spacecraft with unknown orbit elements and inertial tensor

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**Abstract** The state estimation for relative motion with respect to non-cooperative spacecraft in rendezvous and docking (RVD) is a challenging problem. In this paper, a completely non-cooperative case is considered, which means that both orbit elements and inertial tensor of target spacecraft are unknown. By formulating the equations of relative translational dynamics in the orbital plane of chaser spacecraft, the issue of unknown orbit elements is solved. And for the problem for unknown inertial tensor, we propose a novel robust estimator named interaction cubature Kalman filter (InCKF) to handle it. The novel filter consists of multiple concurrent CKFs interlacing with a maximum a posteriori (MAP) estimator. The initial estimations provided by the multiple CKFs are used in a Bayesian framework to form description of posteriori probability about inertial tensor and the MAP estimator is applied to giving the optimal estimation. By exploiting special property of spherical-radial (SR) rule, a novel method with respect to approximating the likelihood probability of inertial tensor is presented. In addition, the issue about vision sensor's location inconformity with center mass of chaser spacecraft is also considered. The performance of this filter is demonstrated by the estimation problem of RVD at the final phase. And the simulation results show that the performance of InCKF is better than that of extended Kalman filter (EKF) and the estimation accuracy of pose and attitude is relatively high even in the completely non-cooperative case.


## 1. Introduction

Estimation of relative motion between spacecraft has attracted extensive attention in the last few years.[1] Especially, it is very important in the rendezvous and docking (RVD) research.[2] RVD is a key technology, which is required for many space

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missions such as assembly in orbit, re-supply of orbital platforms, repair of spacecraft in orbit, etc.[3] The RVD missions which have been implemented so far include orbital express[4], engineering test satellite (ETS)-VII[5] and automated transfer vehicle (ATV).[6] However, most of them are treated as cooperative space missions. Namely, relative estimation algorithm depends on information exchange between spacecraft or some type of beacon preassembled in target spacecraft.[7,8]

In fact, many RVD missions are involved with non-cooperative spacecraft, such as enemy satellite, major in-orbit satellites, etc. In these missions, the estimation of relative motion turns to be more complicated, as there is a little information about pose and configuration of the target spacecraft. And grappling and anchoring to non-cooperative objects is regarded as the top technical challenge in the demonstration mission of NASA flagship technology.[9] In Ref.[10], non-cooperative spacecraft is defined as, "non-cooperative spacecraft means that there is no communication system or any other active sensor, and thus its orientation cannot be determined by electronic inquiry or signal emission".

There is little literature that deals with the problem of relative motion estimation about non-cooperative target. Vision-based estimation of relative motion could be a kind of available solutions for the problem of RVD missions at the final phase. Specially, stereovision technique is widely used in the motion estimation.[11–15] In general, the geometrical characteristic of spacecraft is recognized by vision sensors sampling a sequence of images, such as solar panel, antenna boom, payload attach fitting, nozzle of apogee motor. In Ref.[11], it took four natural features placed on the target satellite to determine relative pose in real time. However, its effectiveness for non-cooperative target is limited, as it supposes that the positions of feature points on target satellite are previously known. Xu et al.[12] proposed a method in which solar panel of spacecraft is identified by Hough transform and provided closed-form expressions about position and attitude of spacecraft. More recently, Liu et al.[13] developed a novel algorithm which is based on information fusion of multi-feature to estimate the pose of non-cooperative satellite. And it takes the contour and nozzle of target satellite as the multi-feature. In addition to the above-mentioned feature-based algorithms, there is another way to determine pose information. In Ref.[14], the relative motion was estimated using a distinctive approach which is named algorithm of mode-based pose refinement. Nevertheless, it needs to take advantage of a prior knowledge of target 3D model and its initial pose estimation. Zhou et al.[15] applied extended Kalman filter (EKF) to estimate the relative states. However, it is not referred to the situation that vision sensor's location does not coincide with the spacecraft's center of mass (c. m.). If the above situation is concerned, a novel kinematic coupling between the rotation and translation will exist.[16] And considerable errors in a rendezvous problem will take place if this perturbation is ignored.

The equations of translational relative dynamics between spacecraft are always resolved in the frame of target spacecraft (e. g., Clohessy–Wiltshire (C–W) equations). However, it is not suitable for non-cooperative applications since the orbit elements of target spacecraft are unknown. In addition, the inertial tensor of target spacecraft is also unknown. The main purpose of this paper is to design a robust filtering scheme for estimating relative motion status with respect to non-cooperative scenarios that both orbit elements and inertial tensor of target spacecraft are unknown. And the issue about unknown inertial tensor is the major consideration in this paper. Actually, this issue can be regarded as a combined estimation problem. In other words, it means that both state variables of system and unknown inertia tensor are estimated simultaneously at the given observations. One approach for combined estimation is to take the scale of unknown inertia tensor as state augmentation.[17,18] However, it just takes the principal moments of inertia into account and does not directly give the value of inertial tensor. Besides, the increase of dimension of the state vector is likely to cause the estimation inconsistency particularly in the nonlinear dynamic system. Another approach is to design an interactive filter, which is either to estimate the state from the unknown parameters or to estimate the unknown parameters from state.[19] Nevertheless, the scheme in Ref.[19] is open-loop and it takes iterated extended Kalman filter (IEKF) which is of low precision and inconsistency for a high-dimensional nonlinear system to estimate state. In this paper, we take the same idea to deal with the problem of the unknown inertia tensor by designing an external estimator interlaced with cubature Kalman filter (CKF). It is proved that CKF is optimal when embedded in the Bayesian filter and its precision and consistency with respect to a high-dimensional nonlinear system are better than those of conventional nonlinear filters,[20] such as EKF, unscented Kalman filter, quadrature Kalman filter, etc. Furthermore, we propose a novel method to estimate the probability density of inertia tensor. As for the issue about the unknown orbit elements of target spacecraft, we take equations resolved in the frame of chaser spacecraft to describe the translational relative dynamics between spacecraft. And the case that vision sensor's location does not coincide with chaser spacecraft's c. m. is also considered.

The rest of this paper is organized as follows: Section 2 presents the model of relative dynamics; Section 3 states the problem of RVD for non-cooperative target; Section 4 presents the algorithm of InCKF; Section 5 gives the numerical simulation results and demonstrates the performance of InCKF for pose estimation; Conclusion remarks are drawn in Section 6.

## 2. Mathematical formulation

Presuppose that two spacecraft are in orbit around the earth. One is the chaser spacecraft with respect to a reference satellite on an eccentric orbit and the other is the target spacecraft in a circular orbit. It is assumed that the chaser spacecraft is equipped with two cameras to capture images of $N$ feature points on the target spacecraft. And the positions of feature points on the target spacecraft are unknown. The relative orbital motion of the two spacecrafts is illustrated in Fig. 1.

In Fig. 1, the following coordinate systems are concerned: $F_{\mathrm{I}}$, the Earth-centered inertial reference frame, whose original $O_{\mathrm{I}}$ is located in the center of the Earth, with the fact that its $X_{\mathrm{I}}$ is pointed to the vernal equinox, its $Z_{\mathrm{I}}$ is directed along the rotational axis of the Earth, and $Y_{\mathrm{I}}$ complies with the right-handed rule; $F_{\mathrm{C}}$, a local-vertical and local-horizontal Cartesian reference frame fastened to the chaser spacecraft c. m., with $X_{\mathrm{C}}$ being a unit vector directed from the center of the Earth to c. m., $Z_{\mathrm{C}}$ towards the direction of chaser spacecraft motion in the chaser's orbital plane, and $Y_{\mathrm{C}}$ completing the dextral triad; $F_{\mathrm{T}}$, a Cartesian right-hand body-fixed reference frame with its