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MCMC-Particle-based group tracking of space objects within Bayesian framework ☆

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Abstract

With the intense increase in space objects, especially space debris, it is necessary to efficiently track and catalog the extensive dense clusters of space objects. As the main instrument for low earth orbit (LEO) space surveillance, ground-based radar system is usually limited by its resolution while tracking small space debris with high density. Thus, the obtained measurement information could have been seriously missed, which makes the traditional tracking method inefficient. To address this issue, we conceived the concept of group tracking. For group tracking, the overall tendency of the group objects is expected to be revealed, and the trajectories of individual objects are simultaneously reconstructed explicitly. According to model the interaction between the group center and individual trajectories using the Markov random field (MRF) within Bayesian framework, the objects' number and individual trajectory can be estimated more accurately in the condition of high miss alarm probability. The Markov chain Monte Carlo (MCMC)-Particle algorithm was utilized for solving the Bayesian integral problem. Furthermore, we introduced the mechanism for describing the behaviors of groups merging and splitting, which can expand the single group tracking algorithm to track variable multiple groups. Finally, simulation of the group tracking of space objects was carried out to validate the efficiency of the proposed method.

Keywords: Bayesian filtering; MCMC-Particle; Group tracking; Space object; Space surveillance

1. Introduction

With the increasing amount of low earth orbit (LEO) space objects, especially space debris, space surveillance has become the foundation for utilizing space resources and avoiding the threats of space debris. Ground-based radar system is the main instrument for LEO space surveillance (Johnson, 2004). Most of the current space surveillance radars can only track and catalog individual space object larger than 10 cm. Here, we mainly concern the objects larger than 1 cm, which can also seriously damage or disable an operational spacecraft. Space debris of small size usually emerges in groups forming high-dense debris cloud (Huang et al., 2012). Unfortunately, the radar system cannot always meet the requirement for resolving and detecting the objects in the space debris cloud due to the resolving capability, object scintillation and occlusion, which makes it difficult to track and catalog the objects individually. However, Instead of the traditional individual object tracking, tracking multiple space objects in group is becoming a potential demand and tendency. In addition, as an important application of space surveillance, collision avoidance is commonly based on calculating the collision probability using the "bulk" of the predicted orbital covariance (Matney et al., 2004). Group tracking describes the "bulk" evolution of multiple closed orbital objects, which just satisfies the need. Group space objects can be defined as the hardly distinguishable objects that have similar orbit

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parameters during the observed period. The undispersed space debris clouds created by orbital collision and the formation of flying satellites possess the typical group character. Tracking or cataloging space objects in group can not only describe the overall evolution, but also potentially improve the accuracy of individual tracks using prior information regarding the group, which has profound significance in space situational awareness and collision avoidance.

Group tracking has some differences with respect to the traditional multiple targets tracking. With regard to multiple targets tracking, the observations are generally matched with the real kinematic states, and the characteristic of individual movements are explicit. However, in group tracking, owing to the dense spatial distribution of the objects in the group, the observations are usually unresolved for the sensors. The information on individual targets will be seriously missed and a higher probability of miss alarm are some of the problems of group tracking. In this case, the overall evolution of the objects obtained from the observation is as important as the individual trajectory. The different tracking problem comprises diverse prior information, solution methods, and so on. Multiple hypothesis tracking (MHT) and joint probabilistic data association (JPDA) filtering (Reid, 1979; Fortmann et al., 1983) are the two classical and effective methods for tracking multi-targets. These methods implement multi-targets tracking based on data association. To alleviate the computational intractability and track the unknown number of objects, (Mahler, 2003) proposed a recursive Bayesian filter for probability hypothesis density (PHD), which is a first-order statistical moment of the multi-target posterior density based on the finite-set statistics (FISST). The PHD filter operates on the single-target state space and avoids the combinatorial problem that arises from data association. Subsequently, Vo and Ma proposed a closed-form solution to the PHD recursion (Gaussian Mixture PHD, GMPHD) for linear Gaussian target dynamics and Gaussian birth model (Vo and Ma, 2006). To derive more stable and accurate estimates of target number, the higher order multi-target approximation filters such as cardinalized PHD (CPHD) and Gaussian Mixture CPHD (GMCPHD) (Mahler, 2007; Vo et al., 2007), were presented in succession. However, the PHD filter does not consider target identity. Furthermore, these methods suffer from performance degradation when the environment is characterized by higher clutter rate and low target detection probability (Ng et al., 2007). Sometimes, tracking the multi-targets as independent individuals hardly improves the tracking performance. Consequently, Khan et al. (2005) incorporated the Markov random field (MRF) to model the interactions between multiple targets. The modifications made could reduce the behavior following which targets may collide spatially. The proposed approach was implemented using Markov chain Monte Carlo (MCMC), and the efficiency was verified by vision-based ant tracking. However, the progress of group tracking was largely hindered by the problems resulting from splitting and merging of groups. Pang et al. (2011) developed a group structure transition model that can describe the splitting and merging of groups smartly, as well as the interaction models for closely spaced targets. They simultaneously tackled the problem of group structure inference and joint detection and tracking for group targets within a Bayesian framework. Furthermore, in the domain of video tracking, general algorithms, such as Mean-shift method (Comaniciu et al., 2003), track the whole object only using the gray probability distribution of the interested area, instead of the individual pixel trajectories.

In practical group space objects tracking, the spatial density of objects does not achieve the pixel density during video tracking, but it usually exceeds the radar's limited resolution for individual small objects. Therefore, in the present study, we have focused on tracking the overall group evolution as well as individual objects trajectory. By analyzing the orbital mechanics of space objects, we have constructed the characteristics parameters for describing the movement and structure of groups. The group objects are tracked within the Bayesian framework. By establishing the interaction model between the nominal group center and individuals, we can not only obtain a more robust estimation of object number and improve the accuracy of the estimated individual trajectory, but also depict the evolution of the groups in the case of low object detection probability. Furthermore, the mechanism for group configuration inference presented in Pang et al. (2011) has been incorporated into our approach, which makes the groups merge and split smartly during the tracking process. Accordingly, the proposed algorithm has real significance for practical application.

The paper is organized as follows. Section 2 describes the kinetic model of space objects, the characteristics parameters of groups, group structure model of the existence state, and the Bayesian group tracking model. Section 3 breaks down the Bayesian tracking procedure into some detailed modules: the state transition model of space object, the state transition model of group center, the interaction model between group center and individual trajectories, and the posterior density model of observation. In Section 4, MCMC-Particle algorithm has been utilized to calculate the Bayesian integral and fulfill group tracking. Section 5 presents the simulation of a single group tracking and analyzes its performance. Section 6 introduces the grouping mechanism, according to which multiple groups have been effectively tracked with the merging and splitting of groups. The tracking performance has been analyzed based on simulation, and the conclusions are presented in Section 7.

2. Bayesian tracking model for group space objects

2.1. Kinetic model and observation of group space objects

Based on the two-body problem, the individual orbit can be fixed according to the three-dimensional position