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Relative navigation for autonomous formation flying satellites using the state-dependent Riccati equation filter

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Abstract

A relative navigation method for autonomous formation flying using the state-dependent Riccati equation filter (SDREF) is presented. In the SDREF, nonlinear relative dynamics, including J_2 perturbation, are parameterized into a state-dependent coefficient (SDC) form without any loss of nonlinearity. The relative navigation algorithm is established based on the carrier-phase differential GPS (CDGPS) and single-frequency GPS data, in which the SDREF is used as a nonlinear estimator. To evaluate the SDREF performance, two different extended Kalman filters (EKF_{R1} and EKF_{R2}) are introduced. The dynamic models of all the filters are based on relative motion including J_2 perturbation. However, the SDREF and the EKF_{R1} use linear state propagation, whereas EKF_{R2} employs nonlinear state propagation. The navigation simulation is performed for each filter using live GPS signals simulated by a GPS signal generator, and the result is analyzed in terms of estimation accuracy and computational load. As a result, the SDREF provides a relative navigation solution with 3-D RMS accuracies of 6.0 mm and 0.153 mm/s for position and velocity, respectively, for a separation of 50 km with a computation time of approximately 34 s. The simulation results demonstrate that the SDREF estimates the relative states as rapidly as the EKF_{R1} and as accurately as the EKF_{R2}, which means that the developed SDREF combines the strong points of EKF_{R1} and EKF_{R2} and overcomes their disadvantages.

Keywords: State-dependent Riccati equation filter; Relative navigation; Spacecraft formation flying

1. Introduction

For spacecraft formation flying, it is essential to determine precisely the position and velocity of a deputy satellite relative to a chief satellite. In particular, it is important to precisely estimate the velocity because accurate knowledge of the velocity reduces orbit control error (Tillerson et al., 2002), which thereby increases fuel efficiency and the mission lifetime. Additionally, it is desirable to autonomously estimate the relative position and velocity using onboard sensors to conduct a mission in real-time or promptly cope with unpredictable situations (i.e., collision avoidance). GPS sensors can be applied advantageously to such an autonomous relative navigation system with inter-satellite communication links (Montenbruck et al., 2002).

Differential processing using GPS carrier-phase measurements allows for precise estimation of the relative position and velocity. The estimation performance is closely related to the characteristics of the filter. For spacecraft formation flying, the extended Kalman filter (EKF) is one of the most important optimal tools, particularly in real-time applications. Many studies in this field have been conducted using the EKF (Leung and Montenbruck, 2005; Gill et al., 2007; Ardaens et al., 2009).

The procedure of the discrete-time EKF can be essentially divided into a prediction step and an update step. During the prediction step, the state and error covariance

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are propagated forward in time. For the state propagation, both a linear state propagation using a state transition matrix and a nonlinear state propagation using nonlinear dynamics equations with numerical integration are available (Alfriend et al., 2010). The former has a small computational burden but reduces the estimation accuracy in a highly nonlinear system. On the contrary, the latter requires a relatively large computational effort but can estimate the parameters more precisely.

Therefore, we need to determine which approach to use by considering the trade-off between the computational burden and the estimation accuracy according to the objective of the application. It is worthwhile to note that the computational burden is no less important than the estimation accuracy in practical applications, particularly when using an onboard system with limited resources available and requiring real-time implementation, such as autonomous formation flying using small spacecraft.

In the current study, the state-dependent Riccati equation filter (SDREF) is proposed as an alternative, which may satisfy both the computational burden and estimation accuracy. The SDREF was first introduced by Mracek et al. (1996) and is based on the state-dependent Riccati equation (SDRE) technique (Cloutier, 1997). In the field of spacecraft formation flying, the SDRE has been continuously used as a nonlinear controller for relative orbit and/or attitude (Chang et al., 2009; Park et al., 2011; Lee et al., 2012; Massari and Zamaro, 2014).

The SDREF is also a nonlinear filter, which estimates states in a similar methodology to the EKF. The only difference is that the EKF is based on linearization, whereas the SDREF is based on a parameterization that transforms the nonlinear system to a linear structure. This allows us to easily deal with a nonlinear system as if it were a linear system. Moreover, there are no linearization effects, and the Jacobian matrix is also not required in the prediction step (Wang, 2011).

As mentioned above, to use the SDREF, a nonlinear system must be converted into a linear structure that has a state-dependent coefficient (SDC) form, which is referred to as SDC parameterization or SDC factorization. Note that in a multivariable case, there are an infinite number of ways to convert the nonlinear equation into the SDC form (Cimen, 2012). However, care should be taken so as not to lose the nonlinearity or induce any singularity during the SDC parameterization.

In the current study, the nonlinear dynamic model, including J_2 orbital perturbation, which is expressed in ECEF (Earth-centered, Earth-fixed) frame, was parameterized into the SDC form without a loss of nonlinearity or any inducement of singularities. In previous formation flying research, SDC forms were typically derived from the nonlinear dynamics expressed in Hill frame (Irvin and Jacques, 2002; Won and Ahn, 2003; Park et al., 2011), which are suitable for control applications for a relative orbit. However, in navigation applications using GPS, because the reference frame (WGS-84) of the GPS is based on ECEF frame, it is more convenient to use equations based on the ECEF frame rather than those based on the Hill frame. Furthermore, no previous SDC form has included J_2 perturbation for relative orbital dynamics except the SDC form of Park et al. (2011), which required the use of the linearized transformation matrix (Gim and Alfriend, 2003) to consider J_2 perturbation. The newly derived SDC form not only practically preserves full nonlinearity but is also less complex than the SDC form of Park et al. (2011).

The relative navigation simulations are performed for formation spacecraft in low Earth orbit (LEO) with the circular formation introduced by Sabol et al. (2001). To validate the developed navigation algorithm in a realistic environment, the orbital dynamics, including full perturbations, are considered and raw GPS data is obtained from the HILS developed by Park et al. (2013), which includes a GPS signal generator and a spaceborne GPS L1 receiver. In addition, two different extended Kalman filters (EKF_{R1} and EKF_{R2}) are introduced to evaluate the estimation performance of the SDREF through a comparison analysis amongst the filters. The dynamic models of all the filters used in the current study are based on relative motion including J_2 perturbation. However, the SDREF and the EKF_{R1} use linear state propagation, whereas EKF_{R2} employs nonlinear state propagation.

The numerous navigation simulations are performed based on various simulation variables, such as the separations between two user satellites and filter design parameters, in which the optimal process noise values for the respective filters are determined. Then, the simulation results employing the optimized design parameters are analyzed for each filter in terms of the estimation accuracy and computation time.

The current study addresses multiple challenges, which are described below. First, the relative navigation algorithm for autonomous formation flying via the SDREF is developed. Second, the SDC form and the linearized equations of relative motion are formulated under J_2 perturbation in the ECEF frame. In particular, the SDC form not only preserves virtually full nonlinearity but also does not have any singularity or ignored terms. Third, to obtain realistic raw GPS data, the HILS consisting of a GPS signal generator and spaceborne GPS L1 receiver is used, which provides a ground-based testing environment to reproduce possible actual spacecraft operations. Fourth, numerous relative navigation simulations are performed and analyzed with a variety of variables, such as various separations between two spacecraft, process noise of a filter, and poor GPS geometry. Lastly, the estimation performance of the SDREF is compared with those of two EKFs to gain insights into the advantages of the SDREF.

The remainder of this paper is organized as follows. Chapter 2 introduces the theory of the SDREF and presents the procedure of an SDC parameterization in detail. Chapter 3 introduces the overall simulation system and presents the simulation environment and configurations.

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