Relative Position Estimation for Satellite Rendezvous and Docking in Low-Earth Orbit

AA 273 Project Proposal

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1 Introduction

Autonomous rendezvous and docking of spacecraft is a key technology for many different missions. Tasks such as on-orbit servicing and cargo resupply[1] are vital to the International Space Station, and to human space exploration in general. Additionally, formation-flying missions, such as TerraSAR-X [2], a global mapping mission, require the ability of several spacecraft to operate in close proximity. At the heart of these operations is knowledge of the relative positions, velocities, and attitudes of all satellites involved. Due to the complicated dynamics and unpredictable disturbances in a space environment, direct position measurements can by noisy. This project will aim to estimate the relative position and velocity of two satellites as accurately as possible, in an effort to increase likelihood of success in close proximity operations.

2 Problem Statement

In order to safely control multiple spacecraft in close proximity, a controller relies on robust estimation of relative spacecraft position and attitude. This project will focus on estimating the relative position of two satellites in low earth orbit (LEO). For the purposes of this project, we will assume relative attitude is known, and disregard control aspect of docking. In this project, we will estimate the relative position of two LEO satellites using both an Extended Kalman Filter (EKF) and an Unscented Kalman Filter (UKF), and compare results.

The state of the system will include the relative positions and velocities of the satellites in Cartesian coordinates: x, y, z, $\dot{x}$, $\dot{y}$, and $\dot{z}$. To make the system Markovian, the state vector will also include the distance from the center of earth, true anomaly, and associated derivatives of the chief satellite: $r, \theta, \dot{r}$, and $\dot{\theta}$. To realistically simulate spacecraft rendezvous, we will use different measurement schemes depending on the proximity of the spacecraft. When the satellites are more than ten meters apart, a GPS-based navigation filtering scheme will be used, with noisy GPS position measurements. When the satellites are closer together, a noisy but direct position measurement can be made using vision systems, providing a noisy measurement of x, y, and z. The reason for switching measurement schemes is discussed in the literature review. It is important to note that the scope of this project only includes rendezvous and docking in LEO, thus GPS measurements will always be available. The final product will include a nonlinear simulation of two satellites in close proximity, as well as an initially uncertain state vector propagated forward by both EKF and UKF estimates.

[1] https://www.nasa.gov/mission_pages/station/structure/launch/overview.html
[2] https://en.wikipedia.org/wiki/TerraSAR-X

3 Literature Review

3.1 Measurement and Sensing

Multiple types of sensors had been implemented on spacecraft for absolute and relative position estimation. Many missions in low earth orbit use a GPS receiver to take advantage of the satellite-based radio navigation system. The GPS satellites broadcast carrier waves with modulation, which the receiver uses to compute its position in 3D. Two types of observation methods are generally used in GPS positioning: the pseudorange observation and carrier phase observation. Pseudorange measurement is obtained by directly measuring signal travel time, which results in a coarse ranging solution. On the other hand, carrier-phase tracking is capable of precision of a few meters. Still, these precision bounds limit the applicability of GPS sensing for close proximity operations [1].

However, due to the small separation between the spacecraft, the carrier-phase differential GPS (CDGPS) technique can be used to obtain relative position of the spacecraft with higher precision by cancelling out the common time bias. Zimmerman demonstrated the feasibility of using the CDGPS technique for rendezvous in a laboratory setting, using pseudolite transmitters and air cushioned robots that can move on a table in 2D [2]. Although the feasibility of CDGPS was demonstrated, the experimental setup is not representative of the highly dynamical environment of space. Corazzini et al. extended Zimmerman's work and conducted a trade study of various estimation algorithms to estimate both relative position and attitude using CDGPS [3]. More recently, Kroes implemented a post-facto relative positioning algorithm using GPS observation data from the GRACE mission [1]. He was able to achieve relative position at millimeter level precision with 220km separation between the two spacecraft, proving that GPS-based relative navigation algorithm can be used in a real world scenario. D'Amico et al. developed GPS-based navigation solution for the PRISMA technology demonstration mission [4]. The PRISMA navigation filter used a combination of pseudorange and single-difference carrier-phase measurements to obtain relative position with four-centimeter precision. The filter also ran on board in real-time.

In addition to CDGPS technique, radio frequency (RF) ranging provides another method for relative positioning between multiple spacecraft. For systems with synchronized clocks, the range measurement can be easily obtained from measuring signal travel time with inter-satellite communication. Allende et al. proposed a sensor fusion scheme to augment differential GPS systems with radio frequency ranging measurements [5]. This sensor fusion method was used to post-process GPS measurements of the PRISMA spacecraft at centimeter level of accuracy. While they did not show any improvements in estimation accuracy, adding another source of measurement increases the robustness of the overall system. Additionally, GPS measurements are not available for missions beyond LEO, thus, RF ranging can be used to estimate relative position between spacecraft. Delpech et al. developed an RF based navigation system for the PRISMA mission and obtained estimation accuracy at centimeter level in simulation [6].

Vision-based systems are often advantageous over CDGPS and RF, as they provide precise orientation measurements in addition to relative position for close proximity navigation. Based on rigid body dynamics, optical relative navigation is possible if at least three points on the target body are known. Junkins et al. proposed a vision-based system called VisNav which uses an optical sensor on the chaser spacecraft and illumination sources on the target spacecraft [7]. The attitude of the target spacecraft can be computed from orchestrating different beacons and measuring the angle to each one of them. However, the target spacecraft must be within the field of view of the optical sensor, so it makes sense to use GPS for spacecraft separation of greater than 10m and switch to vision based navigation system for docking operations. In [7], the VisNav system was simulated from 100 meters to zero range approach and the filter was able to estimate relative position within one centimeter when the separation was within 10 meters and relative attitude within 0.05 degrees.

Other instruments for position estimation includes ground based sensing and magnetometers, but these methods only provide coarse absolute positioning. For example, Shorshi et al. implemented an orbit determination algorithm that only uses magnetometers and obtained absolute position with error of multiple kilometers [8].

3.2 Estimation and Filtering

A significant amount of research has been done weighing the application-specific advantages and disadvantages of various state estimation algorithms. As the rendezvous problem is inherently non-linear, Extended Kalman Filters are commonly used. Kim et al. proposes a way to apply an EKF to both relative attitude and position of two satellites [9]. The relative position of the deputy satellite relative to the chief satellite was represented with a 10-dimensional state vector consisting of: the relative Cartesian distances (x, y, and z), the associated velocities for each axis, the distance of the chief satellite from the center of the Earth and its derivative, and the true anomaly of the chief satellite and its derivative. The orbital dynamics of this state vector are known but not linear, hence the need for the EKF. Wang et al. shows that using an EKF to estimate the relative orbital position of two satellites can be fully observable given the magnitude of the range estimate of the distance between the two satellites [10]. Even more sophisticated work has been done by Zhang et al., who proposed a way to find the relative position even when the initial attitude of the chief satellite was unknown [11], and Sullivan et al. who applied an EKF to find the relative position of another satellite using Keplerian orbital elements and the relative angle of the other satellite [12]. The state vector for the "Angles-Only" representation in [12] is only 6-dimensional, consisting of the difference between each satellite's Keplerian orbital elements. The measurement for the relative position between satellites in this case is simply the measured angle to the deputy satellite from the chief satellite in the coordinate frame of the chief satellite. For this project, our state vector will have same form as [9], due to the simpler translation into relative distance measurements.

Most of the work regarding position-specific estimation between two nearby satellites aims to compare the Extended Kalman Filter to a different filtering algorithm. Crassidis et al. analyzed the problem of two satellites flying in formation, using an EKF for relative position estimation, and Unscented Kalman Filter (UKF) for attitude [13]. Lee et al. extends this work by applying a UKF to the estimation of relative position and velocity as well [14]. Lee et al. developed a suite of simulations to expose each filtering algorithm (EKF and UKF) to different initial conditions, including ideal conditions (no initial bias or error), initial conditions that include some combination of perturbations in position, velocity, bias, or attitude. Their findings suggest that the UKF is more robust under initial error conditions. For example, while the UKF converged to a final estimation when subject to initial position or attitude error, the EKF did not converge at all in the case of an initial attitude error, and converged much slower than UKF when an initial position error was injected [14]. St-Pierre et al. also compared performance between the EKF and UKF applied to the pose estimation of a car driving on a road. They ran numerous Monte Carlo simulations, evaluating each resulting estimation in terms of accuracy/precision, and computational time. The results suggested that, while the UKF produced slightly better results for positioning, it came at a significantly higher computational cost [15].

Corazzini et al. compare the performances of EKF, iterated weighted least squares, and an iterated EKF to estimate formation state of three vehicles in simulation [3]. The simulation included both a static configuration and a dynamic case, both with low-confidence initial conditions. The iterated least squares regularly performed worse in simulation, in both relative and absolution position estimation, than either KF. The iterated EKF provided the same certainty performance as the regular EKF with fewer iterations, but at a price of computational load.

When considering state estimation for spacecraft attitude, several Kalman filter variations have been proposed. Work done in [16], [17], and [18] demonstrates the benefits of Kalman filter variations (Dual Quaternion KF, Multiplicative/Additive EKF, and Pseudo-Linear KF) that utilize quaternions in the state parameter. However, much of the performance gain analyzed in these papers is directly correlated to the representation of attitude estimation in terms of quaternions. Since we have chosen to neglect relative attitude, and instead focus on relative position between satellites in formation, many of these estimation techniques are irrelevant to our project.

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