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Formation flight line of sight guidance[☆]

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ABSTRACT

The purpose of this work is to develop simple control laws based on optical measurements for formation flying. Use of optical navigation is not new and has been used in the past, particularly in the areas of target tracking, interception, rendezvous and docking. Although much work has been done in this field, there are still unique challenges in space applications not faced in the more conventional applications. In this work a leader–follower satellite configuration is considered with the satellites in low Earth orbits. A body fixed configuration for the optical and propulsion system in the chaser satellite is imposed to simplify the actual system implementation for small satellites. Only accelerations normal to the relative line of sight between the satellites are employed. These control laws enable an active chaser satellite to transfer autonomously from one relative elliptical orbit to another, using continuous low thrust engines.

1. Introduction

There are several concepts of future space applications which require operating a satellite cluster in close formation, coordinated together to work as a single virtual satellite. The virtual platform concept enables enhancement of data collection, lowers total mission risk and adds considerable flexibility to the mission. On the other hand formation flying requires increasing complexity in the mission control. Refs. [1,2] present an extensive review of formation flying history and control. The control approaches can be categorized into two main approaches: impulsive and continuous control. Vadali et al. [3] showed that impulsive control is preferred when taking the J_2 perturbations into effect and that in the long run, a two-impulse per orbit strategy is more fuel efficient than continuous thrust for long term formation keeping. Schaub et al. [4] used continuous control to maintain a J_2 invariant relative orbit based on a Lyapunov function to find a nonlinear feedback control law. Starlin et al. [5] showed that control thrust can be applied only in the direction coplanar to the local horizon and that radial thrust in the radius vector direction can be excluded. This simplifies the propulsion system. Shibata and Ichikawa [6] used impulsive control for relative orbit transfer. The follower satellite is placed in a relative orbit described by the periodical solution of the CW equations. The follower then performed an orbit transfer from one relative orbit around the leader satellite to another using a feedback LQR controller.

Most of the published control works used GPS measurement [7]. A few works considered the use of electro-optical means to measure the relative distance and angular velocity between the two satellites. Gurfil and Mishne [8] developed a relative motion control law based on line-of-sight measurements able to maintain a stable cyclic satellite formation. Their work did not consider reconfiguration of the satellite formation. Mishne [9] developed an out-of-plane controller using angular rate information. The control law required knowledge of the out-of-plane position.

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The use of optical navigation is not new and has been used in the past, particularly in the areas of target tracking [10–12], interception [13,14], rendezvous and docking [15]. Although much work has been done in this field, there are still unique challenges in space applications not faced in the more conventional applications. The active satellite observer is in orbit subject to the dynamics and constraints of space flight, the relative distance between the observer and target can range between thousands of kilometers to centimeters while performing a variety of possible relative maneuvers. Furthermore, in the space environment lighting conditions are of a strong varying nature.

The potential of angles-only navigation is greatly enhanced when additional information beyond the standard line-of-sight (LOS) angles, including range and relative attitude information, is obtained from the object's image on the camera focal plane. Recently, Woffinden and Geller [16] developed an angles-only navigation filter to determine relative position and attitude between a passive non-cooperative target satellite and a maneuvering chaser vehicle. In Ref. [17] a model based spacecraft pose estimation and motion prediction using photonic mixer devices was presented.

The main aim of this work is to develop simple control laws based on optical measurements, in order to reduce the complexities involved in satellite formation reconfiguration. A leader–follower satellite configuration is considered with the satellites in low Earth orbits. A fixed configuration for the optical and propulsion system in the chaser satellite is imposed to simplify the actual system implementation for small satellites. The control laws will enable an active chaser satellite to transfer autonomously from one relative elliptical orbit to another, using continuous low thrust engines.

2. Relative motion in polar coordinates

We will consider the case of two vehicles, a passive leader *L* and an active chaser vehicle *F*. A basic assumption in this work is that measurements and control are made in line of sight coordinates. A camera fixed in the follower vehicle tracks the leader vehicle against the sky background. We will further assume that the follower space vehicle has an attitude control system with high enough bandwidth able to maintain the *L* vehicle image in the optical axis. In other terms, the follower vehicle angular position is aligned with the LOS. To control its motion the follower vehicle has a body fixed thruster mounted such that thrust direction is normal to the camera fixed optical axis. A single thruster is enough to apply thrust in a plane normal to the LOS by simply rotating the spacecraft about the LOS direction as shown in Fig. 1.

In order to explicitly take into account the LOS behavior we shall use the relative equations of motion in polar coordinates. The leader is assumed to be in a circular orbit about a spherical Earth. The various systems of coordinates are shown in Fig. 2.

The LOS coordinates are centered in *L*, the passive leader spacecraft and the active follower spacecraft *F* is able to apply accelerations with components a_ρ, a_φ along and normal to the *LF* line of sight. The *F* position is defined by ρ the radius vector along the line of sight and φ, the radius vector direction with respect to the leader radial direction x.

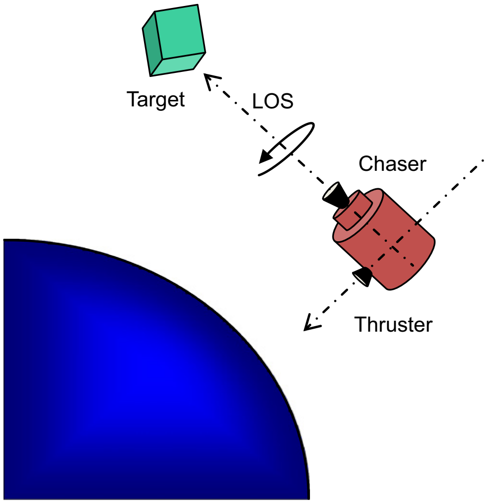

Fig. 1. Target–leader and chaser–follower configuration in LEO.

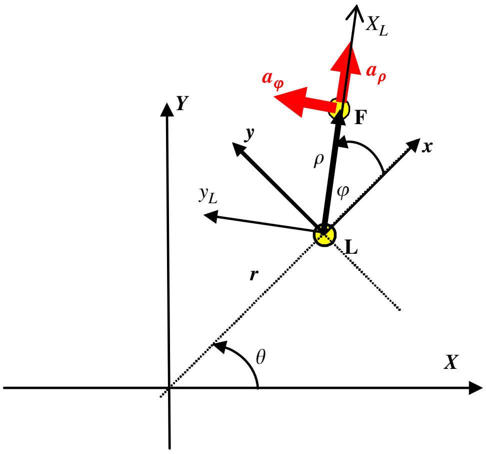

Fig. 2. Formation geometry.

The equations of motion are written in the line of sight coordinates system (x_L, y_L), rotating with angular rate

$$\vec{\omega}_{LOS} = \begin{pmatrix} 0 \\ 0 \\ \dot{\theta}_{LOS} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ n+\dot{\varphi} \end{pmatrix} \tag{1}$$

with respect to the inertial system. n, the orbital rate, constant for a circular orbit, is defined by

$$\dot{\theta} = n = \sqrt{\frac{\mu}{r_1^3}} \tag{2}$$

The following are the relative equations of motion in polar coordinates as developed in Appendix A:

$$\ddot{\rho} - \rho(n+\dot{\varphi})^2 = n^2\rho(3\cos^2\varphi - 1) + a_\rho \tag{3}$$

$$\rho\ddot{\varphi} + 2\dot{\rho}(n+\dot{\varphi}) = -3n^2\rho\sin\varphi\cos\varphi + a_\varphi \tag{4}$$