Acta Astronautica 127 (2016) 131–140

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

Line-of-sight based formation keeping and attitude control of two spacecraft

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ARTICLE INFO

Article history:
Received 13 March 2015
Received in revised form
10 April 2016
Accepted 20 May 2016
Available online 24 May 2016

Keywords:
Spacecraft formation flying
Spacecraft attitude control
Line-of-sight

ABSTRACT

We consider coupled attitude and position control of two spacecraft where absolute attitudes are not available. The objective is to attain a formation requiring a desired distance between two spacecraft and alignment of attitudes along the inertial line-of-sight (LOS) direction between the center of masses of the spacecraft. A relative attitude and position control scheme is developed using LOS vectors measured in each spacecraft's body frame. The current work differs from past research in the sense that the relative positions of the two spacecraft are not assumed to be fixed and all control laws are obtained in respective body fixed frames. The state feedback laws put forth in this work guarantee almost semi-global asymptotic stability of the desired closed-loop equilibrium configuration.

1. Introduction

Space telescopes like Hubble have contributed immensely to enhance our knowledge of the universe. In recent years, there have been several proposals (for example Simbol-X [1], MAXIM [2], and NEAT [3]) for spacecraft formation flying missions with multiple spacecraft in cooperation to function as a powerful virtual instrument. Compared to a monolithic spacecraft, these formation flying missions promise to be more robust and flexible.

However in cooperative missions, maintaining precise relative attitudes and positions are essential for achieving the mission requirements. From a control perspective each of these missions require combined attitude and position control. Most results on attitude consensus and attitude tracking (for example [4]) assume that complete inertial attitude is measured by individual spacecraft and communicated to each other in order to compute relative attitudes. Thus, relative attitude is calculated indirectly by comparing full attitude information, thereby limiting accuracy. Further, instruments for absolute attitude measurements like star sensors are expensive and heavy.

Vector measurements in respective body frames are a convenient way of measuring relative attitudes, without calculating individual absolute attitudes. The concept of attitude determination of a single spacecraft from three independent vector observations in the spacecraft's own frame was proposed in [5], where the authors gave the TRIAD and QUEST algorithms for attitude determination. Line-of-sight (LOS) vector observations between spacecraft can be similarly be utilized for relative attitude determination. These LOS vectors between spacecraft can be measured by standard light-beam focal-plane detector technology or by laser communication hardware as given in [6].

In some cases, even when star trackers are available for inertial attitude measurements, specific relative attitude measurements may be necessary. NuSTAR (The Nuclear Spectroscopic Telescope ARray) mission attempts to measure hard X-ray emission and consists of two telescopes connected by a deployable mast of ten-meter length. In order to compensate the effects of buckling of the mast on measurements, a metrology system is added with lasers and position sensitive detectors (PSD) [7]. The radial flexure of the mast is measured by line-of-sight readings from the position sensitive detector-laser system.

There have been many results on attitude estimation ([8,9]) and control ([10,11]) of single spacecraft using vector measurements in inertial and body fixed frames. Authors in [8] suggest a scheme for determining relative attitude between two spacecraft using line-of-sight measurements to each other and to a reference body. Attitude synchronization of multiple rigid bodies using common vector measurement was discussed in [12]. Cyclic formation control of spacecraft using inertial line-of-sight was proposed in [13]. Authors in [8] also proposed a relative navigation scheme based on line-of-sight vectors. However, contributions in [8] did not include a control design based on line-of-sight information. Attitude determination from vector measurements extends beyond just LOS measurements. In [14], an attitude determination scheme for a nanosatellite was proposed using vector measurements from sun sensor and a magnetometer. Rigid body attitude control of a spacecraft from a single

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http://dx.doi.org/10.1016/j.actaastro.2016.05.025
0094-5765/

vector measurement and gyro information was proposed in [15].

However, there are fewer results on relative attitude control between multiple spacecraft using line-of-sight observations. Authors in [16] propose a control law to asymptotically stabilize the relative attitude between two spacecraft making use of LOS direction observations between them, and to a common object. However, [16] assumes that the vectors measured in the inertial frame are fixed. In reality however, the inertial LOS vary with relative motion of the spacecraft. The resulting variation of inertial LOS with time, would violate assumptions used for stability proof in [16,10] and [11]. This precludes use of the aforementioned control schemes in combined attitude and position manoeuvres of spacecraft in formation flying missions.

In this paper, we consider the following question - can two spacecraft achieve a desired formation and relative attitude in deep space, with no inertial information such as GPS? The results presented here only consider measurements made relative to the spacecraft in a body-fixed reference frame. It is assumed that the two spacecraft have no common reference frame and no access to a third object. Each spacecraft measures LOS vector to the other spacecraft and communicates the same. The control objective is to achieve, attitude alignment about the LOS vector between the two spacecraft and a desired relative distance between the spacecraft. Our proposed control laws are distributed in nature and are obtained in respective body frames. Further, compared to [16] and [17], our work does not assume that the spacecraft center of mass is stationary.

The paper is organized as follows, Section 2 explains the mathematical formulation of the problem, Section 3 describes error functions that are used subsequently, Section 4 gives the control law and stability results for the closed loop system, numerical simulation results are given in Section 5, and conclusions are given in Section 6.

2. Problem formulation

Consider two spacecraft as illustrated in the Fig. 1. Let (x, y, z) be an inertial reference frame and (X', Y', Z') and (X'', Y'', Z'') be body fixed frames of spacecraft one and two respectively.

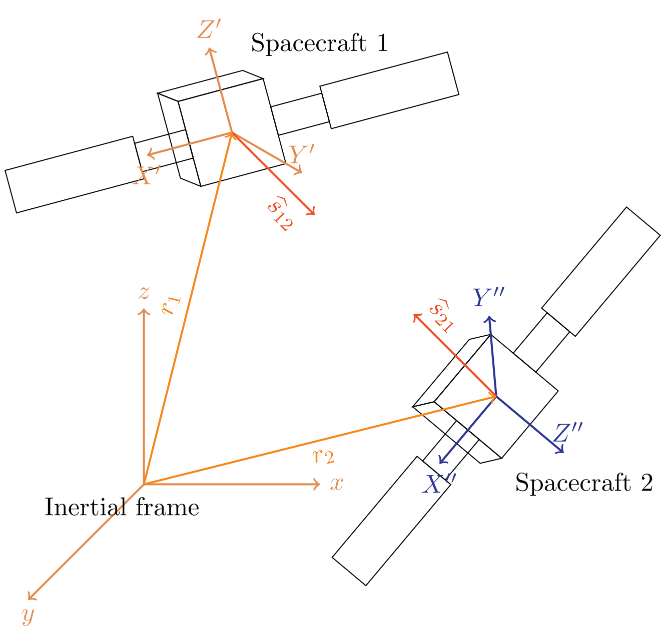

Fig. 1. Two spacecraft in formation: Inertial LOS vectors $\hat{s}_{12}$ and $\hat{s}_{21}$, position vectors r_1 and r_2 of centre of mass of spacecraft 1 and 2 are shown in the figure.

2.1. Dynamics

The attitude of a spacecraft is the orientation of its body fixed frame with respect to the inertial reference frame. This is represented by a rotation matrix in special orthogonal group given as

$$\mathrm{SO}(3) = \left\{ R \in \mathbb{R}^{3\times 3} | R^\top R = RR^\top = I, \det(R) = 1 \right\} \tag{1}$$

The Lie algebra of SO(3) is denoted so(3) and defined as

$$\mathrm{so}(3) = \left\{ S \in \mathbb{R}^{3\times 3} | S^\top = -S \right\} \tag{2}$$

The Euler's equations of motion for the ith $(i=1,2)$ spacecraft's attitude in SO(3) ([18], Section 3.3), are

$$\dot{R}_i = R_i S(\Omega_i) \tag{3}$$

$$J_i \dot{\Omega}_i = J_i \Omega_i \times \Omega_i + \tau_i \tag{4}$$

where $J_i \in \mathbb{R}^{3\times 3}$ are the moments of inertia, $\Omega_i \in \mathbb{R}^3$ is the angular velocity represented in the body fixed frame and $\tau_i \in \mathbb{R}^3$ is the control torque on the ith spacecraft represented in its own body fixed frame. Further, $S(.): \mathbb{R}^3 \to \mathrm{so}(3)$ is the map such that $S(x)y = x \times y$ for any $x, y \in \mathbb{R}^3$. We use the double integrator model for the translation dynamics of the center of mass of each spacecraft, which for the ith spacecraft can be written as, ([19], chapter 12)

$$m_i \dot{r}_i = m_i v_i \tag{5}$$

$$m_i \dot{v}_i = f_i \tag{6}$$

where $m_i \in \mathbb{R}$, $m_i > 0$, is the mass of the spacecraft and $r_i, v_i \in \mathbb{R}^3$ are the position and velocity of the ith spacecraft represented in an inertial frame. $f_i \in \mathbb{R}^3$ is the force applied on the ith spacecraft represented in an inertial frame. It is common to approximate the spacecraft translation dynamics by a double integrator in deep space missions (see [19], chapter 12). Also, our work requires only the relative position dynamics to follow a double integrator. In other words, $r_i(t)$, $v_i(t)$ and $u_i(t)\ (=f_i(t)/m_i)$ need to satisfy the following equations,

$$\frac{d}{dt}(r_1 - r_2) = v_1 - v_2 \tag{7}$$

$$\frac{d}{dt}(v_1 - v_2) = u_1 - u_2 \tag{8}$$

The validity of the double integrator relative translation model for spacecraft in deep space was explored in [20]. As discussed in [20], the double integrator approximation arises from considering two spacecraft in deep space separated by less or equal to one kilometer under combined gravitational forces of the Earth and the Sun [20]. Therefore, for this manuscript, we assume a double integrator relative translation dynamics model.

Define

$$u_i = \frac{f_i}{m_i} \tag{9}$$

where $u_i \in \mathbb{R}^3$ represents the translation control input for the ith spacecraft in the inertial frame. Further, let $x \in \mathbb{R}^n$, then the 2-norm of x is defined as $\|x\| = \sqrt{\langle x, x\rangle}$ and,

$$\frac{d}{dt}\|x\| = \frac{x^\top \dot{x}}{\|x\|} \tag{10}$$