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Close proximity formation flying via linear quadratic tracking controller and artificial potential function

Leonel Palacios*, Matteo Ceriotti, Gianmarco Radice

University of Glasgow, Glasgow, Scotland G12 8QQ, United Kingdom

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Abstract

A Riccati-based tracking controller with collision avoidance capabilities is presented for proximity operations of spacecraft formation flying near elliptic reference orbits. The proposed dynamical model incorporates nonlinear accelerations from an artificial potential field, in order to perform evasive maneuvers during proximity operations. In order to validate the design of the controller, test cases based on the physical and orbital features of the Prototype Research Instruments and Space Mission Technology Advancement (PRISMA) will be implemented, extending it to scenarios with multiple spacecraft performing reconfigurations and on-orbit position switching. The results show that the tracking controller is effective, even when nonlinear repelling accelerations are present in the dynamics to avoid collisions, and that the potential-based collision avoidance scheme is convenient for reducing collision threat.

Keywords: Artificial potential functions; Autonomous control; Collision avoidance; Formation flying; Tracking control

1. Introduction

The idea of autonomous spacecraft flying in tight formation, with maximum separation baselines of a few hundred meters, especially in low Earth orbits (LEOs), has generated widespread interest over the last several years. The constantly evolving notion of spacecraft formation provides the means to enhance mission reliability and adaptability to changing mission requirements by distributing major tasks, which used to be commonly handled by a single monolithic unit, among several smaller spacecraft, therefore leading to technological and economic benefits such as: mission robustness against unit loss by reconfiguring the formation with the remaining satellites, weight reduction in launch payload for tight formation missions, miniaturization and mass production of spacecraft, etc. Moreover, autonomy poses several advantages over traditional manual control, such as the reduction of ground-based orbit maintenance, planning and scheduling by knowing the future position and velocity of the spacecraft at any time and lower propellant usage by continuously maintaining the orbit at its highest level (De Florio et al., 2014). Several autonomous formation flying missions designed to demonstrate the feasibility of this technology are currently deployed while others are still under development, for example, TacSat2 (Plam et al., 2008), Demeter (Lamy et al., 2009), TanDEM-X (Montenbruck and Kahle, 2008) and PRISMA (D’Amico et al., 2013).

Nevertheless, autonomous formation flying presents difficult control challenges which rise in complexity as the number of elements in the formation increases or when proximity operations are required. Having a large number of spacecraft in close formation requires to execute complex maneuvers with minimal fuel consumption and reliable collision avoidance systems. To account for these

* Corresponding author.
E-mail address: l.palacios-moreno.1@research.gla.ac.uk (L. Palacios).

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tasks, several control strategies have been studied; the linear quadratic regulator (LQR) applied to the control of spacecraft information using the Clohessy–Wiltshire (CW) (Clohessy and Wiltshire, 1960) model for circular reference orbits, was used by Starin (2001) where an infinite time cost function was minimized by the algebraic Riccati equation. Bainum et al. (2005) presented further studies where the LQR was used along with the Tschauner and Hempel (TH) (Tschauner and Hempel, 1965) model for elliptic reference orbits. Capo-Lugo and Bainum (2007) used the LQR and the TH model to maintain the separation distance between a pair of satellites for the NASA Benchmark Tetrahedron Constellation. This was accomplished while providing minimum time and fuel consumption through two different approaches, adapting the time-varying term in the TH equations in a piecewise manner and using the TH equations as a time-varying dynamical system. Yoo et al. (2013) presented fuel balancing strategies for maneuvers between projected circular orbits, subject to the CW dynamics, formulating the optimal control problem from Palmer's CW analytical solution for general configurations (Palmer, 2006). Moreover, Huang et al. (2014) used controlled Lorentz forces on an electrostatically charged spacecraft as propellant less electromagnetic propulsion for orbital maneuvering in the planetary magnetic field. For this purpose, a closed-loop integral sliding mode controller was designed to effectively track a trajectory when external disturbances are also present. Artificial potential fields (APF) have been also applied to the control of spacecraft in formation by strongly relying on the theory of dynamical systems. Bennet and McInnes (2008) implemented a control scheme based on attractive/repulsive APF grounded in the theory of bifurcation to command the formation keeping of spacecraft and the transition during maneuvering, providing a wide variety of configurations with only a single parameter change. Badawy and McInnes (2008) used the concept of superquadric potential fields, which allows the accurate modeling of the geometry of any orbital element, for on-orbit assembly of large space structures. McCamish et al. (2007) have also investigated mixed control strategies, such as APF and LQR, to perform rendezvous and assembly maneuvers using the CW relative dynamics near a circular orbit. In nonlinear control with APF, Lee et al. (2015) developed a decentralized, six-degree-of-freedom tracking control scheme using Lie group theory and a Lennard-Jones potential. The simulated scenarios use a virtual leader approach and focus on formation keeping using highly elliptical reference orbits, leading to almost global asymptotic convergence to the desired trajectory.

The objective of this paper is to present the design of a mixed LQR/APF tracking controller for close-maneuvering spacecraft in formation using dynamics of relative motion linearized near an elliptical reference orbit. Contrasted with other LQR/APF formulations, the proposed control strategy has the capacity to deal with both circular and elliptical reference orbits, providing guidance and tracking toward target nominal trajectories while optimizing fuel consumption by Riccati procedure; additionally, the collision avoidance scheme, generated from a Gaussian-like potential function, is defined in terms of both spacecraft and obstacle position and velocity, ensuring evasive actions between the elements of the formation using repelling accelerations. This paper starts presenting first the equations of relative motion to be used, including its state-space representation and energy matching conditions for local bounded relative motion in Section 2. The controller is then presented in Section 3, where the collision avoidance guidance scheme is developed. Next, in Section 4, the selected test cases and results are introduced using elliptical reference orbits. Finally, conclusions are found in Section 5.

2. Linear equations of relative motion

Consider two spacecraft orbiting around the Earth. One of the spacecraft is called leader and the other the follower. Let r and θ denote the radius and the true anomaly of the reference orbit of the leader spacecraft, respectively. In the Local Vertical Local Horizontal (LVLH) reference frame, the linear equations of the relative dynamics of the follower with respect to the leader, in component-wise manner, can be represented as (Inalhan et al., 2002)

$$\begin{aligned}
&\ddot{x} - 2\dot{\theta}\dot{y} - \ddot{\theta}y - \dot{\theta}^2 x = 2n^2\left(\frac{1+e\cos\theta}{1-e^2}\right)^3 x\\
&\ddot{y} + 2\dot{\theta}\dot{x} + \ddot{\theta}x - \dot{\theta}^2 y = -n^2\left(\frac{1+e\cos\theta}{1-e^2}\right)^3 y\\
&\ddot{z} = -n^2\left(\frac{1+e\cos\theta}{1-e^2}\right)^3 z
\end{aligned} \tag{1}$$

with n being the mean motion and e the eccentricity of the reference orbit. A tracking dynamical system, capable of following a nominal trajectory, can be designed in matrix representation using Eq. (1), adding a control input $\boldsymbol{u} \in \mathbb{R}^3$ and a nonlinear term $\mathbf{N} \in \mathbb{R}^6$ to account for external perturbations. With the definition of the tracking vector between the current state $\boldsymbol{x} = [x \;\; y \;\; z \;\; \dot{x} \;\; \dot{y} \;\; \dot{z}]^T$ and the nominal state $\boldsymbol{x}_n = [x_n \;\; y_n \;\; z_n \;\; \dot{x}_n \;\; \dot{y}_n \;\; \dot{z}_n]^T$ as $\delta\boldsymbol{x} = \boldsymbol{x} - \boldsymbol{x}_n \in \mathbb{R}^6$, the tracking dynamics can be represented as

$$\delta\dot{\boldsymbol{x}}(t) = \mathbf{A}(t)\delta\boldsymbol{x}(t) + \mathbf{B}(t)\delta\boldsymbol{u}(t) + \delta\mathbf{N} \tag{2}$$

where $\delta\boldsymbol{u} = \boldsymbol{u} - \boldsymbol{u}_n$ and $\delta\mathbf{N} = \mathbf{N} - \mathbf{N}_n$. The dynamics matrix $\mathbf{A} \in \mathbb{R}^{6\times 6}$ and the control matrix $\mathbf{B} \in \mathbb{R}^{6\times 3}$ are defined as follows (Bate et al., 1971)

$$\begin{aligned}
&\mathbf{A}(t) = \begin{bmatrix} \mathbf{0}_3 & \mathbf{I}_3 \\ \tilde{\mathbf{A}} & \bar{\mathbf{A}} \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} \mathbf{0}_3 \\ \mathbf{I}_3 \end{bmatrix}\\
&\bar{\mathbf{A}} = \begin{bmatrix} 0 & 2\dot{\theta} & 0 \\ -2\dot{\theta} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \tilde{\mathbf{A}} = \begin{bmatrix} a_{41} & \ddot{\theta} & 0 \\ -\ddot{\theta} & a_{52} & 0 \\ 0 & 0 & a_{63} \end{bmatrix}
\end{aligned} \tag{3}$$