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Robust stationkeeping and reconfiguration of underactuated spacecraft formations

Godard, Krishna Dev Kumar*, Anmin Zou

Department of Aerospace Engineering, Ryerson University, 350 Victoria St., Toronto, Ontario, M5B 2K3, Canada

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ABSTRACT

Feasibility of achieving reliable control for spacecraft formation keeping and reconfiguration without the need for thrust in either the radial or along-track direction is explored in this paper. Analysis of the linearized dynamics without along-track input indicates the presence of an uncontrollable eigenvalue at the origin. A nonlinear controller is designed to indirectly stabilize the uncontrollable modes to a stable manifold around the equilibrium. Conditions for robustness against unmatched uncertainties and disturbances are derived to establish the regions of asymptotic stabilization. The benefits of the proposed control method are also validated via numerical simulations to show that precise formation maintenance can be achieved by dealing with the issues of system nonlinearities, variations in initial conditions, and external disturbances, concurrently.
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1. Introduction

Spacecraft formation flying (SFF) has been identified as a key technology to enable advanced space missions [1–5]. Over the past decade, several theoretical and simulation studies pertaining to accurate SFF relative motion models, relative navigation solutions, formation trajectory generation, and formation control have been reported in the literature. Recent advances in spacecraft control systems have succeeded in developing control algorithms capable of high precision formation maintenance and maneuvering in the presence of highly uncertain external disturbances. Most of these control algorithms are developed based on the assumption that the formation geometry is maintained with a sufficient number of thrusters equal to, or larger than, the number of degrees of freedom to be controlled. The loss of thrusters could prove to be disastrous for formation control. Although complete stabilization of the relative positions in all three directions is still possible using redundant thrusters, it is not a viable option due to limitations on mass, power, and financial resources.

Another alternative is to develop a control law capable of achieving full positional control despite losing complete thrust along radial or along-track axis in a standard orthogonal thruster configuration. A design based on this framework must be precise, reliable, and simple enough to allow onboard implementation. Using fewer thrusters in an underactuated configuration poses numerous control challenges in terms of high precision formation maintenance during reconfiguration maneuvers, robustness to external disturbances, and varying orbit conditions. Formation control using no radial thrust has been examined previously based on linearized Hills equations [6,7]. Leonard et al. [6] examined the feasibility of using only along track control input based on open-loop guidance trajectories for controlling the relative position between two spacecraft. The control input was in the form of differential drag between the spacecraft. A bang-bang algorithm based on the control values $-a$, 0, and $+a$, where a is the magnitude of the differential drag acceleration, is considered for achieving rendezvous. This method was improved by Bevilacqua and Romano [8] by proposing a two-phase control method using differential drag for rendezvous maneuvers. Starin

* Corresponding author.
E-mail addresses: ggodard@ryerson.ca (Godard), kdkumar@ryerson.ca (K. Dev Kumar), amzou@126.com (A. Zou).

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et al. [7] considered LQR with no radial axis input. A linear control law is designed to achieve along-track control trajectory for desired projected circular formation based on the follower spacecraft position and velocity relative to the leader spacecraft. Several linear controllers are compared based on performance factors that include the time required to complete the maneuver, the maximum control acceleration, and the total fuel consumed during the maneuver. Theoretical proofs pertaining to stability analysis which are important for investigating the underlying system dynamics were not presented and the closed-loop stability conditions were not stated.

Kumar et al. [9] developed a proportional linear controller using only along track thrust to achieve bounded relative position errors. The control law only requires the estimation of relative along-track position error between the leader and the follower spacecraft. Using in-plane motion and modified Hill-Clohessey-Wiltshire (HCW) equations, Vadali et al. [10] showed that it is possible to achieve a 50% reduction in along-track control acceleration without the use of radial thrust for circular reference orbits. A simple LQR control scheme using an averaging filter is developed to account for formation maintenance. If the selected relative orbit is large enough to create substantial errors between the linear and nonlinear relative equations of motion, linear control algorithms guarantees only local stability. Unmodeled dynamics due to orbit perturbations (J_2) will produce a differential force along the radial axis which cannot be compensated using LQR or proportional linear control when the radial axis thrust is not available. Therefore, nonlinear control based on nonlinear relative model accounting for relative disturbances must be considered to address the global stabilization problem.

In this paper the feasibility of achieving precise three dimensional formation maintenance and efficient formation maneuvering of underactuated spacecraft is investigated using a nonlinear controller. The main contributions of the present work are as follows:

1. A nonlinear control law is proposed based on the leader–follower approach for precise stationkeeping while accounting for relative J_2 perturbations, and large initial position offset errors, that tend to disperse the formation. The proposed controller requires only a radial or along-track thrust, combined with a cross-track thrust to autonomously control the motion of the follower spacecraft from any arbitrary initial condition to a closed stable relative orbit around the leader spacecraft.
2. When no control authority is available in the along-track direction but radial and cross-track thrusts exist, a case not examined in the existing literature on SFF control, the sliding surface is designed to indirectly stabilize the uncontrollable modes via nonlinear feedback to a stable manifold around the equilibrium. The stability conditions for robustness against unmatched uncertainties and disturbances are derived to establish the regions of asymptotic formation stabilization.

The paper is organized as follows: Section 2 introduces the nonlinear mathematical model of the SFF system. A nonlinear controller based on sliding mode technique is designed in Section 3. For a detailed performance assessment of the proposed controller, the results of numerical simulations incorporating different mission scenarios are presented in Section 4. Finally, the conclusions of the present investigation are stated in Section 5.

2. SFF model and system equations of motion

The proposed system comprises of a *leader spacecraft* in an unperturbed circular reference orbit around the Earth and a *follower spacecraft* moving in a relative trajectory about the leader spacecraft. An *Earth Centered Inertial* (ECI) frame is denoted by $\Im - XYZ$, has its origin located at the center of the Earth, with the Z_I-axis passing through the celestial North pole, the X_I-axis directed towards the vernal equinox, and the Y_I-axis completes the right-handed triad (Fig. 1). The orbital motion of the leader spacecraft is defined by $\vec{r_l} \in \mathbb{R}^3$, $\vec{r_l} \triangleq [r_l \ 0 \ 0]^T$ defined in the frame $\mathfrak{B} - xyz$, and true anomaly θ. The motion of the follower spacecraft is described relative to the leader spacecraft using a relative local vertical local horizontal (LVLH) frame $\mathfrak{B} - xyz$ fixed at the center of the leader spacecraft with the position vector, $\vec{r_f} \triangleq [r_l + x \ y \ z]^T$, and the x-axis pointing along the local vertical, the z-axis taken along normal to the orbital plane, and the y-axis representing the third axis of the right-handed frame.

2.1. Equations of motion

In this paper, the spacecraft are modeled as point masses and therefore the rotational dynamics of the leader and follower spacecraft are not taken into account. The nonlinear equations of motion of the follower spacecraft relative to the leader spacecraft taking into account the thrust and disturbance forces can be written in the state space form as follows:

$$\dot{X} = AX + E(X) + BU + DF_d \tag{1}$$

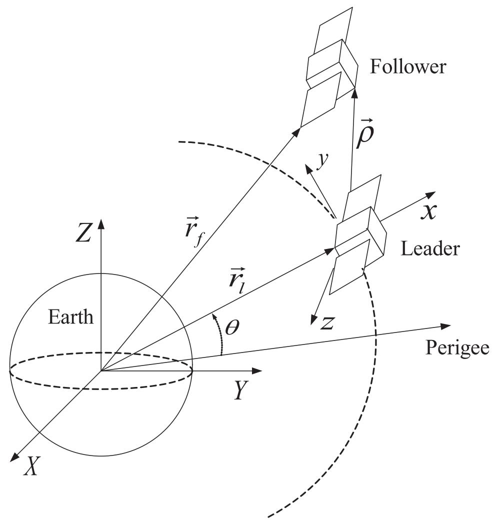

Fig. 1. Geometry of orbit motion of leader and follower spacecraft.

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