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Robust model predictive control for satellite formation keeping with eccentricity/inclination vector separation

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Abstract

This study presents model predictive formation control based on an eccentricity/inclination vector separation strategy. Alternative collision avoidance can be accomplished by using eccentricity/inclination vectors and adding a simple goal function term for optimization process. Real-time control is also achievable with model predictive controller based on convex formulation. Constraint-tightening approach is address as well improve robustness of the controller, and simulation results are presented to verify performance enhancement for the proposed approach.

Keywords: Spacecraft formation flying; Eccentricity/inclination vector separation; Model predictive control; Constraint tightening

1. Introduction

Satellite formation flying is one of the most important research subjects in space engineering (Bauer et al., 1999). Compared to a large single satellite, formation flying offers many benefits including a simpler design procedure, low development cost, short development time, and higher redundancy. However, these favorable aspects do not fully explain why satellite formation is garnering a great deal of attention. Its importance grows rapidly as the number of small satellites increases and distributed system concepts such as synthetic aperture radar or optical stellar interferometers are under consideration. These new concepts contribute to transforming satellite formation from a challenging future technology to real operational issues. For complex mission objectives, proximity operation based on relative states is essential to achieve the required formation between more than two satellites.

There are several approaches to express relative satellite motions. One of the popular methods is Hill's equation (Clohessy-Wiltschire equation as well) based on the circular reference orbit assumption (Clohessy and Wiltshire, 1960). Closed-form solution can be derived from the CW equation since it is linear. Lawden's equation for elliptic orbit (Lawden, 1963) is another option which offers similar benefit of simplicity. The main drawbacks of those approaches are came from the linearized dynamics under simple assumption and the Cartesian states itself which are not directly related to the orbital geometry. Gauss' Variational Equation (GVE) is another way to represent relative motions between two satellites. It is derived based on the Keplerian orbital elements rather than the Cartesian states (Schaub and Junkins, 2003). Although GVE is not dedicated to the relative dynamics, it offers benefits when applied to satellite formations also. For example, large distance of separation can be replaced by small differences in orbital elements. Schaub linearized GVE for mean-orbit elements including J2 disturbances and applied Lyapunov feedback controller (Schaub and Alfriend, 2002). GVE can be extended to other state representations like relative

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Nomenclature

$\Delta\mathbf{e}$	relative eccentricity vector	ε	$J_2(r_{eq}/p)^2 n$
$\Delta\mathbf{i}$	relative inclination vector	r	radius, m
Δe	relative eccentricity vector modulus	r_{eq}	earth' radius, m
Δi	relative inclination vector modulus	μ	earth' gravitational constant
a	semimajor axis, m	J_2	earth' second zonal harmonic coefficient
e	eccentricity	ϑ	Keplerian orbit elements set
i	inclination, deg	χ	relative eccentricity/inclination vector set
Ω	right ascension of the ascending node, deg	ρ	atmospheric density
ω	argument of perigee, deg	C_d	drag coefficient
M	mean anomaly, deg	A	satellite's cross-sectional area
f	true anomaly, deg	m	satellite mass, kg
u	mean argument of latitude, deg	I_{sp}	specific impulse, sec
θ	relative ascending node, deg	$\mathbf{u}$	control input, N
φ	relative perigee, deg	$\mathbf{w}$	disturbance, N
n	mean motion	ϖ	weighting factor
p	$a(1-e^2)$	$P(\mathbf{x}(k), Y, W)$	MPC problem
h	angular momentum	κ	control law

eccentricity/inclination vectors. This approach has been generally adopted for geostationary satellites (Eckstein et al., 1989) with small inclination angles, and D'Amico extends those approaches to low earth orbit satellites (D'Amico and Montenbruck, 2006). Using eccentricity/inclination vectors, an alternative collision avoidance strategy can be implemented by maintaining two vectors in a parallel configuration.

This study presents a model predictive controller (MPC) based on a relative eccentricity/inclination vector separation strategy. To maximize the strength of this state representation, a relevant collision avoidance approach is considered and included in the goal function of the MPC controller. One main reason for the controller selection is real-time control. There are several optimization techniques that can be used in MPC strategy for satellite control, like combining interior-point method and sequential quadratic programming (Chai et al., 2017) or the convex optimization (Boyd and Vandenberghe, 2004). Since this research is conducted based on simple convex formulation, the proposed goal function is convexified to fit into the MPC convergence theory. Although convex relaxation algorithm exists (Misra and Xiaoli, 2017), the simplest first-order approximation is implemented to check the feasibility. For control input, low thrusters such as ion thrusters are assumed since they have a higher specific impulse than chemical propellants, and therefore are more advantageous for small satellites. Smaller fuel mass is required when using such a sophisticated actuators for orbit control. Since only an impulsive control has been addressed (D'Amico and Montenbruck, 2006) using large thrust output in general, continuous dynamics are extended for eccentricity/inclination vectors from GVE dynamics (Schaub and Alfriend, 2002) using state conversion.

The proposed controller is further extended to a robust MPC to consider oscillating terms and possible disturbances as well, because GVE usually adopts mean-orbital elements dynamics, as in the Lyapunov controller (Tillerson et al., 2002). Richards investigated a robust MPC-based on a constraint tightening approach when only the maximum bound of disturbance is given (Richards, 2005). This constraint tightening strategy can be applied to a controllable system, since the tightened margin is derived from state transition matrix. Mean orbital element drift caused by atmospheric drag is also included in the system matrix and to tailor it to the constraint tightening approach, because the linearized GVE matrix based on mean orbital elements is not directly controllable. Using this approach, the robust MPC is applicable to control satellite formations within given constraints even under external disturbances. The robust MPC will guarantee collision avoidance under disturbances, while reconfiguring the formation within the given constraints.

This paper is organized as follows. In Chapter II, Gauss' Variational Equation is expanded for the relative e/i vectors with state conversion from the classical Keplerian orbit elements. This derivation makes continuous control feasible, which is available with low thrusters for instance. In Chapter III, Model Predictive Control (MPC) via convex formulation is proposed to control relative e/i vectors rather than traditional Cartesian coordinate representations. To maximize the benefits of the e/i vector set, collision avoidance from the radial-normal phase difference is also included in the goal function and convexified. Lastly, robust MPC via constraint tightening, introduced in Chapter IV, is adopted to the relative e/i vectors, to take any possible disturbances and the errors from the convexification into account. Since the constraints are tightened based

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