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Attitude synchronization of multiple spacecraft with cone avoidance constraints

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ABSTRACT

In this paper, we consider a team of spacecraft which requires changing its orientation to a common attitude using a decentralized control scheme under a connected communication topology, while satisfying cone avoidance constraints due to blind celestial objects, plume impingement and so on. For this purpose, we first combine consensus theory and optimization theory to develop a quaternion-based attitude consensus protocol. Based on the communication graph at each time step, each spacecraft generates a guidance command or reference attitude trajectory by synthesizing a series of Laplacian-like matrix $\mathbf{P}(t)$, using semidefinite programming (SDP) which involves linear matrix inequalities (LMIs). It is analytically shown that this series of matrices $\mathbf{P}(t)$ is capable of collectively driving the initial attitudes to a common consensus attitude. For satisfying cone avoidance constraints, exclusion zones are then identified and expressed as LMIs. This identification of the exclusion zones gives rise to selecting safe waypoints from the reference attitude trajectory and then to passing through the selected waypoints while avoiding the exclusion zones via proper control inputs. This solution procedure is demonstrated via numerical simulations of coordinated attitude rendezvous and attitude formation acquisition of multiple spacecraft with cone avoidance manoeuvres.

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1. Introduction

Space missions require attitude manoeuvre planning, and many future space missions will involve cooperation and communication among multiple spacecraft. Precise attitude control is of fundamental importance to the success of such missions. The problem of attitude control has been considered extensively. For example, [1,2] study attitude stabilization problems, while [3–6], present some results for attitude manoeuvre control. The attitude control problem becomes more challenging when it involves multiple spacecraft subject to various constraints in dynamic environments, and the spacecraft need to be networked and share certain common objectives. As a matter of fact, various ongoing and future space missions, e.g. Unwin and Beichman [7] and Blackwood et al. [8], require the cooperative navigation and attitude slewing of multiple spacecraft for such purposes as interferometry and optimal sensor coverage.

In [3], a constrained optimization problem involving linear matrix inequalities (LMIs; see [9] for details) is solved for a single spacecraft attitude re-orientation with the sun avoidance (i.e. avoiding a single static exclusion zone). This work is further extended in [6] to two spacecraft with multiple exclusion zones. However, the approach in [6] seems not a viable solution to the problem involving more than two spacecraft, as its computational cost shall increase undesirably fast as the number of spacecraft involved increases.

In a related work in [4], *consensus protocols*[1] are applied in distributed attitude synchronization of a team of communicating spacecraft flying in formation. It is, however, clearly stated in the work that the consensus protocols cannot be directly applied with the nonlinear quaternion dynamics, and the important issue

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[1] *Consensus* in this context is the process of driving some dynamic states (e.g. quaternions) of all communicating spacecraft to a common state in the end. This process often involves a rule of combining the data from neighbouring spacecraft, and this rule is called a *protocol*. Since the spacecraft coordinate their actions by communicating with their neighbours rather than depending on a central planner such as a ground station, this protocol is called *distributed*.

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of avoiding exclusion zones is also not considered. In [5], the *Laplacian matrix*[2] is employed in leader–follower attitude control of multiple rigid bodies using the modified Rodriquez parameters (MRP). However, none of these aforementioned works apply consensus theory directly to quaternions, and none of the other works except [3,6] tackle the important problem of attitude cone avoidance constraints. The works [3,6] still have some drawback in that their techniques are developed for spacecraft sharing the same centre of rotation, which is not true in practice. Another related work [12] has some computational issue that the algorithm breaks down for the problem involving more than two constraints. Therefore, the need for a practical approach to the multiple spacecraft attitude control problem involving cone avoidance constraints is identified and motivates the present work.

In this paper, a new consensus-based approach to constrained attitude control of multiple spacecraft is developed. The method of cone avoidance, originally developed in [3] for a single static exclusion zone, is now extended to cover multiple dynamic exclusion zone avoidance. As will be seen, the multiple dynamic exclusion zone avoidance requires a complex job of handling multiple coordinate frames. Therefore, the unique features of the present work can be summarized as follows: (1) consensus theory which has been mainly used for *translation* is extended to *orientation* control of multiple spacecraft by the introduction of a quaternion consensus protocol; (2) the cone avoidance strategy previously developed for a single static exclusion zone avoidance in [3] is extended to multiple dynamic exclusion zone avoidance, and this extension is incorporated into the consensus framework; (3) mathematical convergence analysis is provided for the developed consensus protocol; (4) a decentralization of the multiple spacecraft attitude control problem is developed, resulting in a new algorithm which reduces computational complexity and has a faster speed of convergence than the approach in [6]; (5) the approach is extended to the practical scenario of multiple spacecraft with their own centre of rotation (instead of the same centre of rotation used in [3,6,12]).

The rest of the paper is organized as follows: In Section 2, the problem formulation for the present work is presented. In Section 3, brief mathematical preliminaries are presented; the solution technique and convergence analysis are provided in Section 4. Numerical simulation results are given in Section 5, and conclusion follows in Section 6. Table 1 shows frequently used notations in this paper.

2. Problem statement

Given a set of spacecraft, with initial states $x^i(t_0) \in \mathbb{R}^3$, $i = 1, \ldots, n$, initial attitude quaternions $q^i(t_0)$, and the Laplacian matrix of their communication graph $\mathbf{L}$, our concern is to drive $q^i(t_0)$ to a consensus attitude quaternion[3] $q(t_f)$, while performing exclusion zone avoidance (avoiding such as blind celestial objects or plume impingement) and satisfying norm constraints. Note that $q(t_f)$ need not be known a priori to any of the spacecraft.

The problem stated above has two major parts: *consensus* and *exclusion zone avoidance*. The consensus part is basically that of driving the attitudes to a consensus attitude. The final consensus attitude is usually the *centroid* (normalized average; to be defined later) of the initial attitudes. But by applying a relative offset quaternion vector $\mathbf{q}_{off}$, the consensus attitude can also be a desired pattern of attitude, e.g. each spacecraft can point 15° away from each other about the z-axis. By applying a leader–follower architecture, or a leaderless architecture with proportional control, the final consensus attitude can also be a set of desired final attitudes for each spacecraft, e.g. SC_1 can be made to point to a particular direction, while various offset angles from the attitude of SC_1 are defined for every other SC. One may think that a standard consensus protocol could be used directly to solve the consensus seeking part of the problem above. However, such a protocol violates the non-linearity of quaternion dynamics and the quaternion norm preserving constraint. Even though a protocol is found which accommodates the quaternion dynamics and the norm preserving constraints, its convergence analysis may not be easy.

Table 1
Frequently used notations in this paper.

SCi, SC_i	Spacecraft i
q^i	Attitude quaternion vector of SC_i, SCi
$\mathbf{q}$	Stacked vector of more than one quaternion vectors
Ω, Π	Quaternion dynamics plant matrix
w	Angular velocity
τ	Control torque
$\mathbf{L}$	Laplacian matrix
$\mathbf{P}$	Laplacian-like matrix
$\mathbf{I}_n$	Identity matrix of size n
$\mathbf{1}_n$	All-one vector of size n
$\mathcal{S}^m$	Set of $m \times m$ positive definite matrices
$\tilde{A}$	Cone avoidance constraint matrix (see (15))
R_i	Rotation matrix corresponding to q^i
$\mathcal{F}^I_{SCi}$	Fixed coordinate frame with origin at SC_i's centre
$\mathcal{F}^B_{SCi}$	Rotational coordinate frame with origin at SC_i's centre
$v^B_{obs_i}$	Vector of exclusion zone in $\mathcal{F}^B_{SCi}$
$v^I_{obs_i}$	Vector of exclusion zone in $\mathcal{F}^I_{SCi}$
$v^I_{obs_i \cdot j}$	Vector of the jth exclusion zone in $\mathcal{F}^I_{SCi}$
$v^B_{cam_i}$	Vector of SC_i's camera in $\mathcal{F}^B_{SCi}$
$v^I_{cam_i}$	Vector of SC_i's camera in $\mathcal{F}^I_{SCi}$
$\otimes$	Kronecker multiplication operator [13]
$\ominus$	Quaternion difference operator (see (9))
$\lVert \cdot \rVert$	Two-norm of a vector or matrix

For the original problem statement to be meaningful practically, the exclusion zone avoidance part must not be neglected. However, as discussed in the previous works [3,6,12], this avoidance part is a computationally difficult optimization problem involving LMI constraints. As the complexity of this problem is greatly affected by the number of LMI constraints, it may not be a good idea that the two parts of the problem statement are posed as a single optimization problem.

For this reason, the following strategy will be proposed later in Section 4. Each part is posed as a separate optimization problem and solved simultaneously at each time step. While the consensus part computes a guidance command for reaching consensus attitude for each spacecraft, the avoidance part decides whether it is safe to track the computed guidance command and generates a proper control input for each spacecraft to track the command. If the guidance command is not safe, the avoidance part computes a new set of quaternion vectors that avoid the exclusion zones and asks the consensus part to compute a new guidance command in the next step. This cycle repeats until consensus is achieved. Unlike the previous approaches in the literature, the guidance command computed by the consensus part satisfies the quaternion dynamics and the norm preserving constraints while guaranteeing the average consensus (see Section 4.1); and the control input generated by the avoidance part is decentralized and also valid in the multiple coordinate frame setting (see Section 4.2).

To illustrate the avoidance part, consider Fig. 1. Denote spacecraft i by SC_i and the unit vector of the camera bore-sight by

[2] The Laplacian matrix $\mathbf{L}$ is used to describe how subsystems in a large-scale system are interconnected. In particular, this matrix can also be used to have the subsystems reach consensus. See [10] or [11] for more about Laplacian.

[3] *Agreement* attitude that all the spacecraft reach in the end. This attitude can also be different among the spacecraft according to a final orientation pattern of interest.

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