An Overview of Research in Distributed Attitude Coordination Control

Long Ma, Haibo Min, Shicheng Wang, Yuan Liu, and Shouyi Liao

***Abstract*—This paper provides an overview of attitude coordination problems of multi-rigid-body with the goal of promoting research in this area. Theoretical results regarding consensus seeking with different system models, different communication topologies, different control goals and different techniques are summarized. And applications of consensus protocols to multi-rigid-body coordination are investigated. Finally, some future research directions and open problems are also proposed.**

***Index Terms*—Multi-rigid-body, attitude coordination, coordination control, consensus, synchronization.**

I. Introduction

COORDINATION control problem of multi-agent systems has received more and more attention in recent years. By transferring and sharing information through communication networks, the agents of the system can be controlled accurately and the whole system will achieve the control goal. Compared with single-agent system, multi-agent systems have special advantages due to its cooperation, such as higher feasibility, higher accuracy, more robustness, easier expandability, lower cost, higher energy efficiency, higher system flexibility and higher probability of success. Currently, there are three kinds of controllers for coordination control problems, i.e., centralized controller, decentralized controller and distributed controller. Both of the first two controllers need a principal controller for global control or local control. However, the distributed one does not need a principal controller, but only a local controller for each agent. Note that some literature have reviewed the coordination control problems. Reference [1] provides a survey of spacecraft formation flying control including five parts, i.e., multiple-input multiple-output, leader/follower, virtual structure, cyclic and behavioral. Some theoretical progress of consensus problems is reviewed in [2], such as convergence and equilibrium state analysis under time-invariant as well as dynamic topologies, information uncertainties, communication delays, consensus synthesis, etc. Reference [3] gives an overview of current applications of cooperative control, e.g., military systems, mobile sensor networks, transportation systems, testbeds, etc, and some of the key technical approaches are summarized, including formation control, cooperative tasking and spatio-temporal planning. Some special consensus problems are introduced in [4], whose underlying state-space is not a linear space, but instead a highly symmetric nonlinear space such as the circle and other relevant generalizations. In [5], some fundamental problems are discussed, such as consensus, rendezvous, flocking and formation, and based upon the characteristics of system dynamics and communication topology, the latest research achievements on coordination control of networked Euler-Lagrange systems are presented intensively.

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On the other hand, spacecraft formation flying (SFF) becomes a new technology that plays an important role in the future space missions such as earth observing (EO)[6−7], orbit express (OE), terrestrial planet finder (TPF)[8], space telescope assembly (STA), stellar imager (SI), synthetic-aperture imaging (SAI)[9], etc. This interest is motivated by the advantages of replacing a traditional large and expensive spacecraft with a cluster of micro-spacecraft to accomplish a common task in a coordinated manner[1].

One of the most important control goal for SFF is attitude consensus or alignment, where every spacecraft updates its own orientation using the orientations of its local neighbors. As a result, the orientations of all spacecraft approach a common value. For example, in interferometry applications[10−11], it is often essential to control different spacecraft to maintain the same or relative attitudes during and after formation manoeuvres. This is a particularly challenging problem in dynamics since the angular velocity of the body cannot be integrated to obtain the attitude of the body[12], which is also the reason why there exist only few papers dealing with this problem in the available literature.

It is well known that the biggest difference between multi-agent system and single-agent system lies in the communication network. Therefore, the characteristics of networks decide the performance of the whole system to a great extent, such as time delays, switching topologies and directed topology. However, the characteristics of the system model are also crucial, such as parametric uncertainties, external disturbances, etc. Furthermore, we also concern about the control goals and the techniques used in the literature.

The rest of the paper is organized as follows. In Section II, we provide basic background of spacecraft attitude dynamics and graph theory. The recent researches on some representative problems of attitude coordination control are reviewed in Section III. In Section IV, we conclude the whole paper and give some future research directions.

II. PRELIMINARIES

A. Graph Theory

Graphs can be conveniently used to represent the information flow between agents. Let $\mathcal{G}=\{\mathcal{V},\mathcal{E},\mathcal{A}\}$ be an undirected graph or directed graph, i.e., digraph, of order n with the set of nodes $\mathcal{V}(\mathcal{G})=\{v_1,v_2,\cdots,v_n\}$, the set of edges $\mathcal{E}\subseteq\mathcal{V}\times\mathcal{V}$, and a weighted adjacency matrix $\mathcal{A}=\{a_{ij}\}$ containing nonnegative adjacency elements a_{ij}. The node indices belong to a finite index set $l=\{1,2,\cdots,n\}$. An edge of $\mathcal{G}$ is denoted by $e_{ij}=(v_i,v_j)$ and it is said to be incoming with respect to v_j and outgoing with respect to v_i. For an undirected graph, $\forall i,j\in l$, if $(v_i,v_j)\in\mathcal{E}(\mathcal{G})$, then $(v_j,v_i)\in\mathcal{E}(\mathcal{G})$, but this does not hold for a digraph. A directed path from node i to node j is a sequence of edges in the form of $(i_1,i_2),(i_2,i_3),\cdots$, in a directed graph. A directed tree is a directed graph, where every node has exactly one parent except for the root, which has directed paths to every other node. A directed spanning tree of a directed graph is a direct tree that contains all nodes of the directed graph. A directed graph has a spanning tree if there exists a directed spanning tree as a subgraph of the directed graph. The set of neighbors of node v_i is the set of all nodes which point (communicate) to v_i, denoted by $\mathcal{N}_i=\{v_j\in\mathcal{V}:(v_i,v_j)\in\mathcal{E}(\mathcal{G})\}$. Graph adjacency matrix $\mathcal{A}=[a_{ij}]\in\mathbf{R}^{n\times n}$, is such that $a_{ij}>0$ if $j\in\mathcal{N}_i$ or $a_{ij}=0$ otherwise. The in-degree of vertex v_i is denoted by $d_i=\sum_{j=1}^n a_{ji}$. Similarly, the out-degree of v_i is denoted by $d_i=\sum_{j=1}^n a_{ij}$. If the in-degree equals to the out-degree for all $v_i\in\mathcal{V}(\mathcal{G})$, then the graph is said to be balanced. $\mathcal{D}=\mathrm{diag}[d_1,\cdots,d_n]\in\mathbf{R}^{n\times n}$ is called the degree matrix of $\mathcal{G}$. The weighted Laplacian matrix of $\mathcal{G}$ is $\mathcal{L}=\mathcal{D}-\mathcal{A}$.

B. Representation of Attitude Dynamics

For a satellite, the attitude information can be measured by attitude determination system composed by gyros, GPS sensors, sun sensors and infrared horizon sensors.

In general, there exist several parameterizations to represent the orientation angles, i.e., the three-parameter representations (e.g., the Euler angles, Gibbs vector, Cayley-Rodrigues parameters, or modified Rodrigues parameters) and the four parameter representations (e.g., unit quaternion). However, the three-parameter representations always exhibit singularity. For example, the Jacobian matrix in the spacecraft kinematics is singular for certain orientations, and it is well known that the four-parameter representations (e.g., unit quaternion) are considered for global representation of orientation angles without singularities.

We only provide the most commonly used presentation of unit quaternion and modified rodrigues parameters (MRPs) here. For more information of the other representations, one can refer to [13].

1) Unit Quaternion: Consider a group of n rigid spacecraft. The motion equations of the i-th rigid spacecraft are given by

$$\dot{q}_i=\frac{1}{2}T(q_i)\omega_i, \tag{1}$$

$$\dot{\omega}_i=J_i^{-1}\left(-\left[\omega_i^\times\right]J_i\omega_i+u_i\right), \tag{2}$$

for $i=1,2,\cdots,n$, where $q_i=\left[\begin{array}{cc} q_{i0} & \bar{q}_i\end{array}\right]=\left[\begin{array}{cccc} q_{i0} & q_{i1} & q_{i2} & q_{i3}\end{array}\right]^{\mathrm{T}}$ denotes unit quaternion that represents the attitude of the i-th spacecraft with respect to inertial frame, $\omega_i=\left[\begin{array}{ccc}\omega_{i1} & \omega_{i2} & \omega_{i3}\end{array}\right]^{\mathrm{T}}$denotes the angular velocity of the i-th spacecraft expressed in the body-fixed frame, $J_i=\mathrm{diag}\left\{\begin{array}{ccc} J_{i1} & J_{i2} & J_{i3}\end{array}\right\}$ and $u_i=\left[\begin{array}{ccc} u_{i1} & u_{i2} & u_{i3}\end{array}\right]^{\mathrm{T}}$ are respectively the inertial matrix and the external input torque of the i-th spacecraft with respect to the body frame. The matrix $T(q_i)$ is given by

$$T(q_i)=\left(\begin{array}{c} q_{i0}I_3+\bar{q}_i^\times \\ -\bar{q}_i^T\end{array}\right)=\left[\begin{array}{ccc} -q_{i1} & -q_{i2} & -q_{i3} \\ q_{i0} & -q_{i3} & q_{i2} \\ q_{i3} & q_{i0} & -q_{i1} \\ -q_{i2} & q_{i1} & q_{i0}\end{array}\right]. \tag{3}$$

Furthermore, we define an orthogonal rotation matrix $C_{Ib}(q_i)$ transiting the body frame into the inertial frame corresponding to the attitude quaternion q_i, which is given by

$$C_{Ib}(q_i)=\left[\left(q_{i0}^2-\bar{q}_i^{\mathrm{T}}\bar{q}_i\right)I_3+2\bar{q}_i\bar{q}_i^{\mathrm{T}}-2q_{i0}\left[\bar{q}_i^\times\right]\right]^{\mathrm{T}}. \tag{4}$$

2) MRPs: Denote $\sigma_i(t)=\left[\begin{array}{ccc}\sigma_{i1} & \sigma_{i2} & \sigma_{i3}\end{array}\right]^{\mathrm{T}}$ as the MRPs of the i-th spacecraft, the motion equations of the i-th rigid spacecraft are given by

$$\begin{aligned}\dot{\sigma}_i&=\Gamma(\sigma_i)\omega_i,\\ \dot{\omega}_i&=J_i^{-1}\left(-\left[\omega_i^\times\right]J_i\omega_i+u_i\right),\end{aligned} \tag{5}$$

where matrix $\Gamma(\sigma_i)$ is given by

$$\Gamma(\sigma_i)=\frac{1}{2}\left(\frac{1-\sigma_i^{\mathrm{T}}\sigma_i}{2}I_3+\sigma_i^\times+\sigma_i\sigma_i^{\mathrm{T}}\right). \tag{6}$$

C. Basic Problems in Attitude Cooperation Control

1) Leaderless Synchronization Problem: The leaderless feature of the algorithms makes them suitable for applications where the particular consensus equilibrium is not important, but rather that each system in the team converges to an identical state. While there are many applications where there exists a group reference trajectory, i.e., leader-following case, there are also numerous applications where leaderless algorithms are important. Examples include rendezvous, flocking, and attitude synchronization. For example, the proposed algorithms have potential applications in automated rendezvous and docking[14].

When no desired attitude is assigned to the spacecraft, all spacecraft are required to synchronize their attitudes to the same attitude. The control goal can be formulated as

$$\begin{aligned}&\lim_{t\to\infty}\|q_i-q_j\|=0,\forall i,j=1,2,\cdots,n,\\ &\lim_{t\to\infty}\|\omega_i\|=0,\forall i=1,2,\cdots,n,\end{aligned} \tag{7}$$

where $\|\cdot\|$ denotes the norm of a vector.

2) Leader-follower Problem: A constant desired attitude, represented by the unit-quaternion q_d, is available to a single spacecraft as a leader. All spacecraft are required to synchronize their attitudes to the desired attitude, which can be named as regulation case. The control goal can be formulated as

$$\lim_{t\to\infty}\|q_i-q_d\|=0,\forall i=1,2,\cdots,n,$$
$$\lim_{t\to\infty}\|\omega_i\|=0,\forall i=1,2,\cdots,n. \tag{8}$$

If given a dynamic desired attitude with the angular velocity denoted by ω_d, all spacecraft are required to synchronize not only their attitudes to the desired attitude but also their angular velocities to the desired angular velocity. This is called dynamic tracking case, which can be formulated as

$$\lim_{t\to\infty}\|q_i-q_d\|=0,\forall i=1,2,\cdots,n,$$
$$\lim_{t\to\infty}\|\omega_i-\omega_d\|=0,\forall i=1,2,\cdots,n. \tag{9}$$

3) Formation Problem: Formation is to realize a special geometric architecture by controlling every spacecraft, which can be described as

$$\lim_{t\to\infty}\|q_i-q_j-q_{dij}\|=0,\forall i=1,2,\cdots,n,$$
$$\lim_{t\to\infty}\|\omega_i-\omega_d\|=0,\forall i=1,2,\cdots,n. \tag{10}$$

III. Representative Attitude Coordination Control Problems

A distributed controller for attitude synchronization is beneficial for practical uses such as satellite surveillance, pointing control, formation flying and space based interferometry. The advantages of using a distributed attitude controller are to avoid a complete redesign of the control system when new subsystems are added, and to guarantee the stability of the whole system[15−16]. There are some conditions we should consider in dealing with attitude coordination control problems as follow. To describe the relative attitudes between different spacecraft, the linear expression is simple, while the nonlinear form has a clear physical meaning and can be easily transformed to other attitude representation schemes. With global inertial frame information, the controller design is convenient, while the condition with no global inertial frame information but only relative attitude information is more practical. State feedback or output state feedback in controller design should be choosen according to the practical scenario. Consensus tracking control for a group of spacecraft is more challenging if only a subset of group agents have access to the virtual leader[17]. Furthermore, another challenge is the design of reliable systems that are able to provide good performance even in the presence of uncertainties and faults[18]. Moreover, obtaining global asymptotic stability of rigid-body attitude is a fundamental and difficult task.

In this section, we divide the attitude coordination control problems into five sub-problems, such as system models, communication topologies, control goals, special strategies and others, and this section can be summarized as Table I.

A. System Models

1) Parametric Uncertainty and External Disturbance: Parametric uncertainty and external disturbance are common characteristics of multi-rigid-body systems. For example, due to the change in mass properties, there exists uncertainty in the inertia matrix, analogously, due to the manufacture technics, there exist external disturbances in the actuators or magnetorquers. To solve this problem, variable structure control, sliding mode control method and H_∞ control method are effective.

A simple distributed variable structure coordinated controller is proposed in [19] to solve the attitude coordination control problem, with the presence of model uncertainties, external disturbances and time varying communication delays. By constructing a sign function with an auxiliary vector and designing the control law without using the information of inertia matrix, the rejection of model uncertainties and external disturbances is realized. In particular, [20] presents a general framework for synchronized multiple spacecraft rotations via consensus-based virtual structure. In this framework, both parametric uncertainty and external disturbance are taken into consideration, and a time-varying sliding mode control (TVSMC) algorithm is designed to improve the robustness

TABLE I
REPRESENTATIVE ATTITUDE COORDINATION CONTROL PROBLEMS AND METHODS

Problems	Categories	Methods
System models	Parameter uncertainty and disturbance	Variable structure, sliding mode, H_∞ control
	without angular velocity measurement	Constructing filter, observer, auxiliary vector
	Time delays	Lyapunov-like method
	Fault-tolerance	Neural networks and fuzzy logic method
	Input saturation	Introducing saturation function
	State constraints	Geometric algorithms, potential function,etc.
Communication topology	Fixed topology Switching topologies	Common Laypunov function
Control goals	Optimal control	Cost function
	Containment control	Sliding-mode estimator
	Finite time control	Finite-time sliding mode, Bang-Bang, sign function
Special strategies	Parameter uncertainty and disturbance	Variable structure control Fuzzy predictive control Neural networks

of the actual attitude control system. As an alternative to the virtual structure approach, a class of distributed coordinated attitude control laws using behavior-based control approach are proposed in [21]. In order to reject the model uncertainties and external disturbances, a term composed by a sliding vector is derived. By converting the attitude dynamics to Euler-Lagrange equations, [22] gives another auxiliary vector, based upon which a distributed discontinuous adaptive controller is designed to reject the effect of external disturbances. Different from the above literature, [23] develops two robust adaptive algorithms to handle the effects of unmodeled dynamics and unknown inertia matrices of agents. The first one is based on modification method which traps the trajectories of the system into a small neighborhood around the origin. In the second algorithm, the effects of external disturbances are removed by using a discontinuous function. Moreover, [24] proposes a filtered robust adaptive attitude coordinated controller to overcome the case with input constraint, model uncertainties, and external disturbances.

On the other hand, [25] presents an adaptive fuzzy mixed H_2/H_∞ attitude control method, and the effect of external disturbance and fuzzy approximation error on spacecraft attitude can be restrained and the tracking error as well as consumed energy of the controller is minimized. Based on linear time-periodic models and H_∞ control theory, [26] proposes an approach guaranteeing robustness to parametric uncertainty and optimal performance in terms of disturbance attenuation.

Note that the parametric uncertainty problem can be solved in two ways. One is to design the control law without using the information of inertia matrix J_i, in which the control law has the following form

$$u_i = -k_i^p q_i - k_i^d \omega_i - \sum_{j\in N_i} a_{ij} q_{ij} - \sum_{j\in \mathcal{N}_i} a_{ij}\omega_{ij} - u_{di}, \quad (11)$$

where k_i^p and k_i^d are both positive constants, q_{ij} is the attitude error between the i-th agent and the j-th agent, u_{di} is the robust term. Another way is to linearly parameterize the unknown nonlinear part of the function, i.e.,

$$N_i(\omega_i, \dot{\omega}_{di}) = -\omega_i^{\times} J_i \omega_i - J_i \dot{\omega}_{di} = Y_i(\omega_i, \dot{\omega}_{di})\theta_i, \quad (12)$$

with

$$\theta_i = (J_{i11}, J_{i12}, J_{i13}, J_{i22}, J_{i23}, J_{i33})^{\mathrm{T}}, \quad (13)$$

where $Y_i(\omega_i, \dot{\omega}_{di})$ is the polynomial of ω_i and $\dot{\omega}_{di}$.

To solve the external disturbance problem, we can add a robust term in the control law, i.e., $u_{di} = \lambda_i \mathrm{sgn}(\omega_i + q_i)$ in (10), where λ_i is the upper bound of the external disturbance.

2) Without Angular Velocity Measurement: In the application of spacecraft formation control, when the whole system is configured without angular velocity sensor for low cost and small volume, or angular velocity sensor conks out, the control strategy should be designed without using the information of angular velocity. This problem can be solved by constructing a proper filter, a model-based observer or an auxiliary vector.

Regulation Case. In [27], to solve this problem for attitude control of a rigid body, the angular velocity feedback is replaced by a nonlinear filter of the quaternion, rather than a model-based observer reconstructing the velocity. Reference [28] further considers the problem in the presence of an unknown inertia matrix. Using a full-state feedback controller, not only parametric uncertainty is compensated, but also angular velocity measurements is eliminated. Thereafter, the work of [22] is extended to synchronized multiple spacecraft rotations control problem in [29] with a passivity-based damping method. Based on nonlinear observers and vectorial observer backstepping, [30] proposes a Leader/Follower output feedback synchronization scheme for control of the attitude of two satellites when angular velocity measurements are not available. As an extension, [30] presents a solution to the problem of tracking relative rotation in a leader-follower spacecraft formation using feedback from relative attitude only. The controller incorporates a linear approximation filter to achieve knowledge of angular velocity, and the controller structure renders the equilibrium points of the closed-loop system uniformly practically asymptotically stable (UPAS). However, [30−31] only consider a two-body problem, and the solutions cannot be used to multiple rigid-body problems. In [32], a distributed control algorithm for attitude coordination of spacecraft formation without angular velocity feedback is presented. The advantage of this algorithm is that it requires limited information exchange among the spacecraft in the formation (only attitude information exchange is necessary). In addition, [33] proposes a leader-follower-type control scheme for the attitude synchronization of a spacecraft formation to a desired constant attitude (available only to a single spacecraft, the leader), while maintaining the same attitude during formation maneuvers, and also proposes another scheme with no reference attitude, by constructing an auxiliary system for each spacecraft. Similarly, [34] also uses the auxiliary system to solve the distributed attitude alignment control of spacecraft within a formation without angular velocity measurement, however only the regulation case is considered.

Dynamic Tracking Case. References [35−36] extend the result of [34] to dynamic tracking case, where the desired angular velocity is not zero. Enlightened by the work of [27] and [34], [37] uses both a distributed sliding-mode estimator and a passivity approach to derive a control law without angular velocity measurements, with modified rodriguez parameters (MRPs) for attitude representation. To consider more complicated case, unknown mass moment of inertia matrix and external disturbances are added into the attitude dynamics. In a related work in [38], an adaptive neural controller is proposed via incorporating a filtering technique to generate a pseudo-velocity tracking error signal from attitude angle measurements into the exiting adaptive neural network control scheme using the Chebyshev neural network, and converting attitude dynamics to Euler-Lagrange dynamics. However, it is restricted to the condition that all the followers know the attitude state of the leader. Particularly, [39] derives a control law that guarantees a group of spacecraft to track a time-varying reference attitude without requiring velocity measurements even when the common reference attitude is only available to a subset of the group members. As an extension, [40] discusses attitude tracking and synchronization problem without angular velocity measurements as well as with input constraints, and gives a controller design for this problem. Using a low-pass linear filter state, which is derived without explicit differentiation of attitude to synthesize angular velocity-like signals, [41] proposes a controller for satellite formation flying without using explicit absolute angular velocity or relative angular velocity feedback, and with unknown communication non-uniform various time-delays.

3) Time Delays: In practical applications, time delays inevitably exist in the system and communication links, which may degrade the control performance of the formation and even destabilize the entire system. Lyapunov-like method is effective for time delay problems, i.e., constructing Lyapunov-Krasovskii function, Lyapunov-Razumikhin function and Set-valued Lyapunov function.

Reference [18] proposes a simple distributed variable structure coordinated controller with Lyapunov′s directed method for multiple spacecraft attitude coordination control problem in the presence of model uncertainties, external disturbances and time-varying delays in the intercommunication. However, the restriction $T_{ij} = T_{ji}$ denoting the nonnegative constant communication time delay from the j-th spacecraft to the i-th spacecraft, is conservative. With constant time delays, [42] designs two control laws that can guarantee attitude synchronization with zero and non-zero final angular velocities respectively. Using Euler parameters to represent the attitude deviation between spacecraft, [43] proposes a new PD-type attitude synchronization control algorithm, and a new tool called Tree Expanding approach is developed to show the convergence of the attitude synchronization errors, with which attitude synchronization is indeed achieved without requiring any assumption of the spacecraft orientations. In particular, [44] proposes a virtual systems-based approach that removes the requirement of the angular velocity measurements, based upon which the leaderless and leader-follower problems with time-varying communication delays and undirected communication topology, and the leaderless problem under directed topology and constant communication delays are all solved. Then, [45] extends this to solve the cooperative attitude tracking control problem. Alternatively, [46] deals with the problem of cooperative attitude tracking with time-varying communication delays as well as the delays between inter-synchronization control parts and self-tracking control parts in the spacecraft formation flying, and more specifically, a class of linear filters are developed to derive an output feedback control law without having direct information of the angular velocity. Moreover, [47] develops an cooperative attitude control scheme with model uncertainties, external disturbances and variable time delays, and the novelty of this approach lies in the strategy to construct such a Lyapunov function scarifying the L_2-gain dissipative inequation that ensures not only the stability of a cooperative attitude tracking formation system but also an L_2-gain constraint on the tracking performance. Reference [48] addresses the robust adaptive coordinated attitude control problem (CACP) for formation spacecraft with model and disturbance uncertainties, and especially with unknown constant time delays. Unlike existing designs, where constant delays must be explicit and bounded, the proposed novel laws solve the CACP with disturbances and unknown/large constant communication delays by injecting a nonlinear term. Different from the existing literature which describe the delayed relative attitude via linear algorithm, [49] develops a new control law with the nonlinear nature of the employed quaternion based attitude coupling. As an alternative, [50] treats the attitude error and the local relative attitude on the nonlinear manifold-Lie group, and attempts to obtain coupling attitude information by the natural quaternion multiplication. However, most of the literature only consider the problem with undirected topology.

4) Fault-tolerance: Another challenge is the design of reliable controllers that are able to provide good performance even in presence of faults. Most traditional attitude fault-tolerant control reconfiguration techniques rely on failure detection and isolation. However, neural networks and fuzzy logic systems can be used to the design of nonlinear fault tolerant controllers.

Reference [51] presents a distributed adaptive fuzzy approximation design to achieve attitude tracking control for formation flying in the presence of external disturbances and actuator faults. A nonsingular fast terminal sliding mode controller based on consensus theory is designed for distributed cooperative attitude synchronization, and a fuzzy logic system (FLS) is introduced to approximate unknown individual satellite attitude dynamics due to actuator faults. In [52], a class of distributed adaptive fault-tolerant attitude coordination control laws are proposed to achieve high-attitude tracking and synchronization performance, even in the presence of an unknown mass moment of inertia matrix, bounded external disturbances, actuator failures, and control saturation limits.

5) Input Saturation: Control input saturation due to the limited capacity of actuators is a major problem in attitude control laws design. When control input saturation occurs, the dynamic performance of attitude control system goes bad, and even worse, the whole closed-loop system will become unstable, which is very harmful. In order to solve input saturation problems, either introducing a saturation function or properly choosing the control parameters is effective.

Reference [53] presents a continuous globally stable tracking control algorithm for spacecraft attitude control problem in the presence of control input saturation, parametric uncertainty, and external disturbances. Applying anti-windup control and intelligent integrator to minimize reaction wheel type actuator saturation, [54] presents a spacecraft large angle attitude control strategy with actuator saturation limit. By choosing the control parameters properly, [55] presents a nonlinear control scheme to deal with input saturation. In particular, [56] addresses a quaternion-based attitude regulation control for rigid spacecraft subject to input constraints. By introducing hyperbolic tangent saturation function into the control scheme, input saturation problem can be restrained effectively. However, only a single spacecraft attitude control problem is considered in the above references. Based upon the results in [56], [57] studies the coordinated attitude control problem of satellite formation consisted of two satellites, which is further extended in [58] to finite-time case. In another related work [59], a solution to the problem of formation reconfiguration and maintenance for fleets of micro-satellites in the presence of persistent disturbances and under input-saturation and formation accuracy constraints is proposed. The proposed control scheme is based on a bank of controllers composed by primal LQ control laws, which compensate the system without taking into account the presence of constraints, and nonlinear CG units, which are used to generate a suitably modified version of the reference signal, capable of producing evolutions that fulfil the constraints at each time instant. Extending the results in [31], [60] considers quaternion-based attitude synchronization and tracking problem for spacecraft formation with actuator constraints as well as without measurement and exchange of angular velocities among spacecraft in the formation. Reference [61] deals with the input saturation problem by incorporating a low-pass command filter such that the generated control law could be implementable even under physical or operating constraints on the control input. In particular, [62] introduces a new continuously differentiable nonlinear saturation function vector in order to guarantee the boundedness of control input. Furthermore, [63] considers a more complicated case that only a subset of the group members has access to the common reference attitude, and a quaternion-based distributed attitude coordination control scheme is proposed for attitude coordination control problem with consideration of the input saturation and with the aid of the sliding-mode observer, separation principle theorem, Chebyshev neural networks, smooth projection algorithm, and robust control technique.

6) State Constraints: For formation flying of multiple spacecraft missions with sensitive pay loads, such as cryogenically cooled infrared telescopes, the slew maneuver must be achieved without directing the payload along the sun vector or at other infrared bright regions of the sky[64]. Therefore, studying attitude coordination control problem with attitude constraints is very meaningful. In general, there exist some methods to solve this problem, e.g., geometric algorithms, potential function-based algorithms, constraint monitor algorithms, randomized algorithms, semidefinite programming-based algorithms, etc[65].

In [66], Yoonsoo Kim′s team considers the attitude control problem augmented with an arbitrary number of non-convex quadratic constraints. By utilizing the implicit magnitude constraint of the state vector (i.e., quaternion), they reduce this problem to a convex quadratically constrained quadratic program or a semidefinite program, which leads to an efficient solution strategy for general quadratically constrained attitude control problems. It is worth noting that, this is about a single spacecraft attitude re-orientation with the sun avoidance (i.e., avoiding a single static exclusion zone). This work is extended in [67] to two spacecraft with multiple exclusion zones. However, the approach in [67] seems not to be 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. Based upon [66] and [67], [68] considers a team of spacecraft which require changing their orientation to a common attitude using a distributed control scheme under a connected communication topology, while satisfying cone avoidance constraints due to blind celestial objects, plume impingement and so on. However, this kind of choice and decision scheme needs abundant calculation.

It is worth mentioning that, [69] derives a kind of navigation function, which is very useful when obstacles avoidance is involved. Reference [70] designs a navigation function based upon the results in [69], and proposes an algorithm based on the navigation function and backstepping method for the attitude maneuver of spacecraft under pointing constraints. Thereafter, [71] develops a method for controlling spacecraft large slew maneuvers with sun vector avoidance, while [72] considers the trajectory optimization for satellite reconfiguration maneuvers with attitude constraints. In [73], a predictive control algorithm based upon the construction of positive definite Hessian matrix is presented for spacecraft attitude maneuver with non-convex geometric constraint together with bounded inputs. Another algorithm based on the navigation function of line-of-sight and back-stepping method is presented in [74]. Considering the attitude constraint problem during spacecraft attitude tracking in [75], quaternions are used to describe the region of forbidden attitude, and a new Gauss avoidant potential function is proposed using the minimum angle allowed by the forbidden attitude, by which a safe attitude maneuver controller is obtained. However, all the aforementioned papers rely on the case of a rigid body.

We can see that there are few literature concerning about the attitude coordination control with obstacles avoidance, and this will be an interesting research topic.

B. Communication Topologies

1) Fixed Topology: The communication topology is static.

Fixed and undirected topology. Reference [44] solves the leaderless and leader-follower problems under fixed and undirected communication topology. We see that undirected graph gives a symmetric Laplacian matrix, which makes it convenient to design the control law, while directed graph does not.

Fixed and directed topology. In [76], a cooperative attitude tracking problem is addressed under directed information exchange, where a group reference attitude is available to only a subset of the group members. However, the analysis for attitude tracking in [76] is restricted to the case where the directed graph can be simplified to a graph with only one node. It is not clear whether the conclusion still applies to a general directed graph. Then, [77] considers distributed attitude synchronization for multiple rigid bodies with Euler-Lagrange equations of motion. Reference [78] extends this work to incorporating a time-varying reference attitude, where the reference attitude is allowed to be available to only a subset of the group members under general directed information exchange. Particularly, [79] designs a distributed coordinated tracking algorithm which guarantees all followers to track the leader and extends the distributed control algorithm to guarantee that the spacecraft maintain constant relative orientations with their neighbors. In [80], a distributed adaptive sliding-mode control law is designed by introducing appropriate multi-spacecraft sliding-mode vector, which includes attitude error and angular velocity error of individual spacecraft, as well as relative attitude errors and relative angular velocity errors between spacecraft. As an alternative, [81] addresses the distributed attitude synchronization problem of multiple spacecraft with unknown inertia matrices, and two distributed adaptive controllers are proposed for the cases with and without a virtual leader. However, the attitude dynamics is converted to Euler-Lagrange form. Moreover, [82] provides distributed linear kinematic control laws for the problems that the agents measure their own orientations in a global reference frame and the agents only measure the relative orientations to their neighbors respectively.

2) Switching Topologies: Communication outage, new member′s joining or quitting, radio silence or recovery will cause the change of the communication topology, named switching topologies, which makes it more difficult to design the control laws.

Switching and undirected topologies. Based on relative attitude information and Modified Roodriguez Parameters, [36] considers cooperative attitude tracking problem and gives a control law in the presence of a dynamic communication topology. Reference [83] extends this to the condition that there exist both multiple time-varying communication delays and dynamically changing topologies, and the result of uniformly ultimate boundedness of the closed-loop system is obtained. Considering more complicating elements, [84] presents controllers that can render a spacecraft formation consistent to a given trajectory globally with dynamic information exchange graph and non-uniform time-varying delays while coping with the parameter uncertainties and unexpected disturbances. In [85], a 6-DOF dynamics model of the spacecraft formation flying is established in Euler-Lagrange form, and a control algorithm based on consensus theory is proposed in the presence of dynamic communication topology. Furthermore, almost-global attitude synchronization is achieved in [86] based on switching joint connection, however auxiliary variables are introduced which make the controllers complicated. In [87], by utilizing Lyapunov direct method and choosing a common Lyapunov function properly, the robustness of the designed position and attitude coordinated controllers to communication delays, switching topologies, parameter uncertainties and external disturbances is guaranteed.

Switching and directed topologies. It is worth mentioning that, [88] addresses the attitude synchronization problem of multiple rigid body agents in SO(3) with directed and switching interconnection topologies. Using the axis-angle representation of the orientation, a distributed controller is proposed based on relative orientations between the agents without a global reference coordinate frame. In the case that each agent can only measure the attitudes of its neighbors from the body-fixed frame of the agent, a distributed protocol is proposed in [89] provided that the inter-agent topology graph is jointly connected and each relative attitude between agents initially is contained within a geodesic ball of radius less than $2\pi/3$ centered at its desired relative attitude. From the viewpoint of interior metrics, [90] provides a consensus protocol for strongly convex geodesic balls and applies it to the consensus problem of rotation attitudes under switching and directed communication topologies.

We see that, to solve the switching topologies problem, we usually choose a common Lyapunov function to guarantee the robustness of the whole system. Moreover, the parameter-dependent Lyapunov function may be useful for the distributed control design, which can reduce the conservation of using a common Lyapunov function.

C. Control Goals

1) Optimal Control: With the development of aerospace mission, it is badly in need of control strategy for spacecraft with less power and faster speed, which makes the spacecraft attitude maneuver optimal control problem a serious one.

There are some literature studying attitude optimal stabilization of a rigid body, e.g., [90−96] control the satellite to a particular attitude with a minimum amount of fuel, while [97] and [98] investigate attitude maneuver with a minimum time, to name just a few.

However, there are few researches about multi-rigid-body attitude coordinated control with less fuel or less time. This will be a very interesting research direction.

2) Containment Control: Distributed attitude control problem becomes more challenging when it involves multiple leaders (which can be called as attitude containment control), however it is very useful in practice, e.g., earth monitoring, astro observation, coordinated target attack with multiple warheads [99], etc. Under these circumstances, some spacecraft (i.e., leaders) are set to form an objective area, and the other spacecraft (i.e., followers) are rendered within this area to enlarge the monitoring field, observation scope or killing radius.

Reference [100] studies the containment control problem in mobile networks. Reference [99] extends the results in [100] to the case of rigid body attitude containment control, but only discusses the case of multiple stationary leaders with asymptotic rather than finite-time convergence. When there exist multiple dynamic leaders, a distributed sliding-mode estimator and a non-singular sliding surface are given to guarantee that the attitudes and angular velocities of the followers converge, respectively to the dynamic convex hull formed by those of the leaders in finite time in [101]. However, the attitude dynamics is converted to Euler-Lagrange form, which is not straightforward enough to attitude control. In [102], for the case of undirected angular information topology and directed angular velocity information topology, a containment control algorithm based on relative angular and relative angular velocity is proposed, and the constrained conditions for the angular velocity information topology to ensure containment objective are obtained by using algebraic graph theory. However, only the regulation case is addressed.

Note that there are only few researches considering the attitude containment control problem with dynamic leaders, time delays, switching topologies, parametric uncertainties, and directed topology. This will be another future research direction.

3) Finite Time Control: Compared with asymptotic convergence, finite-time convergence is more useful in practical application. Sliding mode control (SMC) algorithm can be used to achieve this objective.

References [103−104] give a few forms of terminal sliding modes and terminal sliding mode estimators respectively, both of which are very useful for designing finite-time control laws. With terminal sliding mode, [105] proposes two control laws to drive a rigid spacecraft to reach a given desired attitude in finite time in the presence of model uncertainties and external disturbances. Using terminal sliding mode and Chebyshev neural network, a finite-time tracking control scheme is proposed for attitude tracking control of one spacecraft in [106]. It is worth to mention that, there are some errors in [106], which are corrected by [107]. Based on the attitude dynamics representation of Modified Rodriguez Parameters, a distributed finite-time attitude control law is proposed for a group of spacecraft with a leader-follower architecture in [108]. In [109], a novel fast terminal sliding manifold is presented, and a robust control term based on the hyperbolic tangent function is applied to suppress bounded external disturbances under fixed topology. It is worth mentioning that, [110] develops a class of continuous sliding mode control schemes with finite-time convergent property under arbitrary communication topologies. Based on the behavior approach, an improved version of terminal sliding mode is applied in both the reaching phase and the sliding phase of the control system. In the presence of external disturbances, the proposed control strategies are able to overcome the unexpected phenomenon, and can steer the spacecraft formation to a dynamic reference attitude state coordinately. As an extension, [111] investigates the robust distributed attitude control problem for spacecraft formations with model uncertainties and external disturbances under uncertain communication topologies, and based on modified Rodrigues parameters representation and a Lagrange-like model, a class of distributed attitude control schemes designed by the use of sliding mode control approach are proposed to steer the attitude of the spacecraft formation to a time-varying reference states. In addition, [112] considers multi-spacecraft finite time attitude regulation control problem with a directed communication graph, while [113] considers this problem with input constraints. Combining the strategies of finite-time control, fast terminal sliding mode (FTSM) control and adaptive control, a novel distributed finite-time control law is proposed in the presence of inertia uncertainties and environmental disturbances under the general directed communication topology in [114], which ensures that each spacecraft can attain the desired time-varying attitude and angular velocity in finite-time while maintaining attitude synchronization with other spacecraft in the formation. Furthermore, in [90], a consensus protocol for strongly convex geodesic balls is proposed to solve the consensus problem of rotation attitudes with switching and directed communication topology.

Besides of SMC method, Bang-Bang control method and scaled sign function method[115−117] are both appropriate for distributed finite-time consensus problems.

D. Special Strategies

1) Variable Structure Control: Variable structure systems have been a major control design methodology for many decades. The term variable structure systems was introduced in the late 1950′s, and the fundamental concepts were developed for its main branch sliding mode control by Russian researchers Emelyanov and Utkin[118]. When parameter uncertainties and external disturbances exist, sliding mode control method is very helpful. To some extent, sliding mode control is equal to variable structure control.

In [119], a kind of adaptive sliding mode contro1 algorithm is proposed in presence of severe nonlinearity, inertia matrix uncertainty and external disturbances during the large attitude angle maneuver of a spacecraft. With sliding mode control algorithm, [120] and [121] introduce controllers to achieve high performance on the attitude tracking under the actuator saturation. The second and third order quasi-continuous sliding control are applied to quaternion-based spacecraft attitude tracking maneuvers in [122], however can only realize first-order sliding-mode dynamics because of the improperly chosen sliding vectors. Then, some alternative measures to realize second-order and third-order sliding-mode dynamics are suggested in [123]. All the above literature are about attitude control of a single rigid spacecraft, but sliding mode control is also applicable for distributed attitude synchronization problem. Under the assumption that the relative position and attitude are known, a fully distributed variable structure-based relative attitude-coordinated control law is proposed in [124], which can efficiently minimize the relative attitude error in the presence of model uncertainties and environmental disturbance torques, and achieve the attitude coordination among the multiple satellites flying in formation. In [125], a multi-spacecraft sliding manifold is derived, on which each spacecraft approaches the desired time-varying attitude and angular velocity while maintaining attitude synchronization with the other spacecraft in the formation. Translating attitude dynamics into Euler-Lagrange form, [126] designs a distributed robust controller with sliding mode to guarantee that the attitude errors between the followers and the leader converge to zero for any communication graph containing a directed spanning tree with the leader being the root.

2) Fuzzy Predictive Control: Another efficient method for compensating model uncertainty and external disturbances is adaptive fuzzy predictive control algorithm. Formulating the attitude dynamics with quaternion, an adaptive fuzzy logic systems is constructed, based upon which, a direct adaptive fuzzy predictive control method is presented for attitude tracking of satellites with model uncertainty and external disturbances in [127]. In [128], the direct adaptive fuzzy robust control is applied to the attitude stabilization control of the satellite, and the parameters of fuzzy rules in FLS can be adjusted so that the proposed method has on-line adaptive ability.

3) Neural Networks: Reference [129] introduces back propagation learning algorithm with feed forward neural networks, and [130] uses this method for function approximation. We know that neural networks have emerged as a powerful learning technique to perform complex tasks in highly nonlinear dynamic environments. Recently, some literature have investigated the problem of output feedback attitude control of a single spacecraft and multiple spacecraft formation based upon neural networks (NN)[131−132] and Chebyshev neural networks (CNN)[38−39,63,106,133−135], which have much significance for edification.

E. Others

Screws theory[136] combines translation and rotation simultaneously. Dual quaternion is the most succinct and effective way to represent screws dynamics[137], which has been used in both the dynamics and kinematics analysis of many research areas, such as spatial mechanisms[138], robots[139], rigid bodies[140], to name just a few.

Reference [141] deals with simultaneous position and attitude robust maneuver problem of a rigid spacecraft, and proposes a control strategy using backstepping technique that enables the spacecraft to track reference position and rotation motions in a finite time. Reference [142] addresses the synchronized control problem of relative position and attitude for spacecraft, and a new adaptive sliding mode control scheme is proposed to guarantee the globally asymptotic convergence of relative motion despite the presence of control input constraint, parametric uncertainties and external disturbances. In [143], a specified rooted-tree structure together with a dual quaternion solution to attitude and position control for multiple rigid body coordination problem are proposed. We can see that, there are few literature about multi-rigid-body systems coordinated control based on dual quaternion. This may be another research hotspot in future.

In [9], a class of nonlinear H_∞ attitude controllers are proposed to stabilize a satellite at a desired attitude or angular velocity, which is useful in practical application. Reference [144] considers the problem of autonomous synchronization of attitudes in a swarm of spacecraft, and removes the singularity and confusion by modeling the spacecraft as articles on SO(3) and driving these particles to a common point in SO(3). Reference [145] addresses passivity-based motion coordination of rigid bodies in the special Euclidean group SE(3) rather than special orthogonal group SO(3), under the assumption that the agents exchange information over strongly connected graphs. To handle the non-linearity of the dynamic system, the problems of absolute and relative attitude dynamics are formulated as the state-dependent Riccati equation (SDRE) in [146−147], based upon which, distributed coordinated attitude control algorithms are developed. Reference [148] investigates cooperative control strategies for spacecraft formations, also in case that platforms are not homogeneous but differ in attitude control actuators, such as thrusters, momentum exchange devices (momentum wheels, reaction wheels, etc.), and magnetic actuators. Converting the attitude dynamics to Euler-Lagrange form, [149] studies adaptive attitude synchronization of spacecraft formation with possible time delay, parameter uncertainties and unknown external disturbances. In [150], a hybrid feedback scheme is proposed relying on the communication of a binary logic variable between each pair of neighboring rigid bodies that determines the orientation of a torque component actuated to reduce their relative error. Through a hysteretic switch of this logic variable, the hybrid feedback achieves global synchronization under the assumption that the network is connected and acyclic. Reference [151] develops a gradient coupling law for attitude synchronization with partial state coupling on the Lie group SO(n), while [152] proposes a hybrid-dynamic algorithm for smoothly lifting an attitude path to the unit-quaternion space, which removes the limitation of unit quaternion and guarantees global asymptotical stabilization of the attitude of a rigid body. Different from the other literature, by extending the case of fixed-gains in the synchronization signal, [153] considers two cases in which the local weights of the synchronization signal can differ for each spacecraft (node-dependent gains) and differ for each spacecraft and for each of its communication neighbors (edge-dependent gains). Moreover, [154] proposes a control scheme, which is directly developed on special orthogonal group(SO(3)) to avoid ambiguities and singularities associated with the attitude representation of Rodrigues parameters or unit quaternion.

IV. Conclusions and Future Directions

We have reviewed distributed attitude coordination control problems for multi-rigid-body systems in the current literature. As a new research area, the study of attitude coordination control is still incomplete, and there remain some problems to be solved.

The first problem is complex network. In current literature, most research assumes that there exists only communication delays. The case with both communication delays and self delays is a key branch of research in the future. The second is attitude coordination problem with state constraints, e.g., with the sun vector as one static constraint, with multiple static or dynamic constraints, and it is also interesting and challenging. Furthermore, the control with less fuel consumption or less time is also of importance, however, there are few literature concerning these issues, which will be another research direction.

Obviously, rigid-body attitude dynamics is not like the single or double integrator dynamics, but all of them belong to the same kind of problem. The research hotspot of the single and double integrator systems will be the one of the rigid-body systems. Several interesting problems to be addressed are as follows.

1) Should we choose constant edge-dependent synchronization gains or use adaptive edge-dependent synchronization gains? How to optimize the synchronization gains?

2) In many practical multi-agent systems, consensus regulation performances and control energy consumptions should be considered simultaneously. How to get the guaranteed-cost consensus?

3) Except for system disturbances, there are some other kinds of uncertainties in multi-agent networks, which have significant influence on the success of coordination algorithms and performances of the whole network. For discrete-time models, the distributed stochastic approximation method is introduced in [155−157] to attenuate the impact of communication/measurement noises and conditions are given to ensure mean square and almost sure consensus. For continuous-time models, [158] gives a necessary and sufficient condition on the control gain to ensure mean square consensus. Reference [159] deals with mean square consensus problems for linear multi-agent systems communication noises. Reference [160] makes a systematic study of unstable network dynamic behaviors with

white Gaussian input noises, channel fading and time-delay. Furthermore, computational expressions for checking mean square stability under circulant graphs are developed in [161]. References [162−163] study the distributed consensus with additive random noises for discrete-time and continuous-time models, respectively. Most of the above literature focus on the first or second order linear systems. In rigid-body systems, how to solve the problem that the distributed consensus corrupted by communication noises?

According to the research goal, attitude coordination method is to provide a guidance to the practical application. The work on how to use these theoretical results to solve the real-life problems, deserves our effort. Currently, this research is mainly taken as a theoretical rather than an engineering problem. Another key problem is how to model the research objects more precisely. Considering different communication topologies, together with different control goals, and making the scenario more close to the real world condition, is also a meaningful direction.

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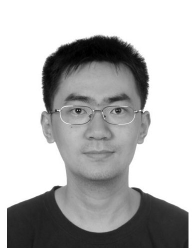

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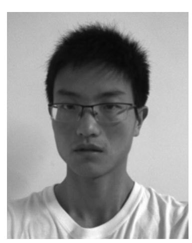

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