INVITED PAPER

A Survey on Formation Control of Small Satellites

This paper comprehensively reviews the state-of-the-art development in formation control of small satellites including satellite formation flying, distributed satellite systems, and fractionated satellite formation.

By Guo-Ping Liu, *Fellow IEEE*, and Shijie Zhang

ABSTRACT | This paper comprehensively reviews the state-of-the-art development in formation control of small satellites. Satellite formation flying, distributed satellite systems, and fractionated satellite formation are discussed first. Various formation control architectures and methods of small satellites are then introduced, including the leader-following method, the behavior-based method, the virtual structure method, the cyclic pursuit method, the artificial potential function method, the algebraic graph method, and the noncontact force method. Coordinative control of multiple small satellites is also reviewed, covering coordinative control of satellite formation, coordinative attitude control of satellite formation, and coordinative coupled attitude and orbit control of satellite formation. The achievements and development trends of the formation control of small satellites are considered and analyzed.

KEYWORDS | Coordinative control; formation control; satellite formation; small satellites

I. INTRODUCTION

In the last century, human beings successfully entered into the space and made a great contribution to the progress of social civilization. At present, the space technology and applications have brought many changes in various fields. So far, more than 4600 satellites (artificial satellites) orbiting Earth have been launched and successfully applied to communications, navigation and positioning, meteorology, environmental and disaster monitoring, marine exploration, and other fields [1]. Most of these achievements are based on a single satellite, which is the main force in applications of satellites. From the current development of space technology on the whole, the development of satellite technology leads to two different trends. One is the weight and size of a single satellite become heavier and larger, and its structure and functions are more complex. The other is small satellites with various structures and their functions are relatively simple through coordination work to replace complexity of a single large satellite. Because of the complex technology, long development cycle, and high cost, the development of large satellites is limited. On the other hand, with the development of new energy, new materials, and new communication technology, the coordinated control system composed of many small satellites through the networking mode presents a booming trend [2].

Satellite formation flying is an important mode of multiple small satellites, in which each satellite remains in a stable close distance configuration, mutually maintains close connection, and shares signal processing, information exchange, payload, and other functions [3]. This mode is the main means of realizing the space-based interferometric synthetic aperture imaging, gravity field measurement, space optical virtual imaging applications, etc. Since the 1990s, the concept of multisatellite formation flying has conducted a number of space flight demonstrations and applications of satellite formation technology for astronomy, communications, meteorology, and environmental uses [4]. The advantages and significance of satellite formation technology and its applications have been validated. In recent years, with the development of space technology and space mission, satellite formation research category has been expanded. A traditional integrated satellite is decomposed into small payload modular satellites and small service modular satellites, which form a virtual space system via wireless *ad hoc* networks. In terms of requirements of task aggregation or separation, a separation-cluster satellite system is formed, which can effectively improve ability of dealing with uncertainty,

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G.-P. Liu is with the School of Engineering, Faculty of computing Engineering and Science, University of South Wales, Pontypridd CF37 1DL, U.K. (e-mail: guoping.liu@southwales.ac.uk).
S. Zhang is with the School of Astronautics, Harbin Institute of Technology, Harbin 150001, China (e-mail: sjzhang@hit.edu.cn).

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enhance quick response ability, and reduce difficulty of entering the space. It is one of the most important directions of the development of international space technology.

To make full use of satellite formation technology advantages, it greatly depends on coordinative control performance of the formation and distributed information fusion capability of each satellite, which is also necessary for the normal operation of the whole satellite formation. This is one of the key problems of satellite formation. Whether it is the coordinative control of satellite formation or the fusion of satellite information, it is necessary to realize information exchange between satellites through networks, which results in a networked satellite formation system. The cooperation of satellite formation forms a virtual satellite that replaces a single large satellite, achieves its equivalent functions, and completes some tasks that cannot be done in a certain extent. The coordinative control system of the networked satellite formation is a distributed space system, which is composed of satellites that are independent from each other, has local communication networks, and realizes a common space mission [5]. The satellites share information via communication links on satellite networks and achieve consensus on the system target tasks through the principle of consistency. The satellite formation accomplishes control tasks of the whole system using common navigation and control through mutual coordination between individual satellites.

Coordinative control methods and technologies of networked satellite formations will have a profound impact on space science and technology and its applications. It is fundamentally changing technical approaches of the existing satellite missions, which has incomparable advantages with existing satellites. The main points are as follows [6]–[9].

- System cost reduction: Since the whole system completes a space mission through coordination of a number of small satellites, the design and manufacture of those small satellites can be done using standardized processes and the cost of production becomes lower. Due to the small size and light weight of the small satellites, their launch costs will be greatly reduced. In addition, when a small satellite in the system fails, it can be replaced with a low cost in a short period of time and then the maintenance cost of the entire system is reduced. In short, the adoption of networked small satellites to replace an original large satellite can reduce the total cost of space missions significantly.
- System performance improvement: As the networked satellite formation consists of multiple satellites, the information and resource redundancy considered in the system design can enhance the robustness and fault tolerance of the system. Also, it can strengthen autonomous navigation and control of satellites, realize automatic assignment and coordination of space mission tasks, reduce dependence on ground stations, and improve autonomy and intelligence of the system. At the same time, the parallel and distributed nature of a networked formation system can improve the efficiency of the whole system.
- System reliability enhancement: The coordinative control design of a networked satellite formation system can be modularized through standardizing inter-satellite links, communication interfaces between small satellites, and control algorithms. A system for special space tasks can be developed using the above. Moreover, if the space environment and tasks are more complex or a small satellite in the system is damaged, only a few links related to it will be affected and the whole system will not collapse.

The coordinative control methods and technology of networked satellite formations involve the related knowledge and technology of information theory, artificial intelligence, control science, and experimental science. The inspiration from and the applications of the above theory and technology will establish a theoretical and technological foundation for satellite formation flying, separation-cluster satellite systems, and aerospace systems, and also play an important role in theoretical research and applications of satellite formation flying. At the same time, it also promotes the development of multidisciplines, and makes the space technology serve the human civilization better.

Small satellites generally refer to satellites with the weight of less than 500 kg, which can be subdivided into minisatellites (100–500 kg), microsatellites (10–100 kg), nanosatellites (1–10 kg), picosatellites (0.1–1 kg), and femtosatllites (<100 g) [10]. In particular, the emergence of micronanosatellites (1–30 kg) represented by cubic satellites has initially achieved the standardization and batch development of satellites. In recent years, the number of launches has increased rapidly, more than 200 per year. Russia successfully launched 37 tiny earth remote sensing satellites into orbit by a Dnepr rocket in 2014 and 72 small satellites by Soyuz- 2.1a rocket in 2017, mainly for commercial remote sensing and weather constellations of four different companies. Then, China and India successfully launched 20 small satellites from a rocket in 2015 and in 2016, respectively. Recently, India launched 104 satellites and 31 satellites from a single rocket at a time by the India polar orbit satellite launch vehicle PSLV in 2017 and 2018, respectively. Most of the satellites launched by India belong to small satellites.

Compared with the spacecraft formation, the satellite constellation has longer distance between satellites, expands the scope of service space and takes global service as the main target of a class of distributed space systems, such as the U.S. GPS, Russia GLONASS, European Galileo, China BeiDou. The Global Positioning System (GPS) project with 24 satellites was launched by the U.S. Department of Defense in 1973 for use by the U.S. military and became fully operational in 1995, which was allowed for civilian use in the 1980s [11]. The Russian global navigation satellite system (GLONASS) was first developed in the Soviet Union period and then was continued by Russia [12]. In 1993, Russia began to establish its own global satellite navigation system alone. The system opened only Russian satellite positioning and navigation services in 2007 and then was extended to the world in 2009. The main services of the system include determining the coordinates of land, sea, and air targets and moving speed information. Currently, GLONASS satellites in orbit have reached the number of more than 30. Galileo is the global navigation satellite system with 30 satellites created by the European Union [13]. After the Galileo test satellite in 2005, the first Galileo satellite was launched in 2011. Galileo system started offering early operational capability in 2016 and is expected to reach full operational capability in 2019. BeiDou is a global satellite navigation system developed by China, which is made up of five geostationary satellites and 30 nongeostationary satellites [14]. The first BeiDou satellite was launched in 2000 and BeiDou has now covered the Asia Pacific region and will cover the whole world by 2020.

The concept of satellite formation proposed in the 1970s has not gained too much attention because a large satellite system is complex and expensive and has a long development cycle, which has usually limited the number of formation satellites. Since the late 1990s, the modern small satellites have been developed rapidly with mature technology, low cost, and mass production. As the small satellites have restrictions on size, weight, and functions, multisatellite formation plays its best mode performance. So, the combination of small satellite technology and formation flying technology promotes the development of small satellites. Compared with the formation of traditional large satellites, the formation of small satellites has a much larger scale, the communication topology is more complex, the relative sensor configuration is incomplete, and the functions are limited. Therefore, the new concept of satellite formation is needed, which will greatly expand the research field of satellite formation.

Over the past 30 years there has been much research on the control of spacecraft formation. In the areas of space-based synthetic aperture imaging, optical imaging, gravity measurement, and astronomical observation, a number of formation flying programs have been developed, such as terrestrial planets observation, synthetic aperture radar for Earth observation, and formation flying technology demonstration plans. The U.S. Air Force Research Laboratory (AFRL) proposed the TechSat-21 plan in 1998, aimed at the small spacecraft formation of a distributed radar system for Earth observation. The German Aerospace Center (DLR) achieved the Earth's gravity field measurement (GRACE) and space-based interferometric synthetic aperture radar imaging (TanDEM-X) in 2002 and 2010, respectively. Sweden tested the key technology of PRISMA formation in 2010. China launched Shi Jian-9 (SJ-9A) satellites and completed the satellite formation flying and high precision GPS in 2012, having validated the establishment and maintenance technology of satellite formation. The formation of satellites in orbit validating significant formation advantages and application value is also a part of the programs. But some programs have been canceled because the difficulty is too hard. On the other hand, it illustrates the complexity of formation system technology. It is necessary to review the research results in this field and to provide the technical means and new research directions for the follow-up research.

II. SATELLITE FORMATION FLYING

The concept of satellite formation flying was proposed by Sholomitsky *et al.* in 1977, who used multiple satellites to perform interferometric infrared synthetic aperture imaging [15]. In the 1990s, with the development of modern small satellites and the breakthrough of intersatellite relative measurement and control technology, satellite formation flying has attracted more attention [16], [17]. In the space-based synthetic aperture radar (SAR) interferometric imaging [18], synthetic aperture optical imaging [19], gravity field measurement [20], astronomical observation [21], and other fields, various plans for satellite formation flying were formulated (e.g., terrestrial planet finder [22], [23], earth observation using SAR [24], and formation flight demonstration [25]). Moreover, relevant basic theories and key technologies have been studied, and partial verification and applications of them have been carried out in orbit.

In recent years, satellite formation flying technology has expanded to new application fields, for instance, the high-orbit high-resolution optical Earth observation requires the ultrahigh aperture and ultralong focal length optical systems formed through precise satellite formation [26]; on-orbit service of spacecraft needs to fly around a noncooperative target and achieve attachment to it [27]. The concept and range of satellite formation flying are also widening [28], [29], such as electromagnetic force formation [30], Coulomb force formation [31], ultralarge cluster flight [32], the Confederacy space system [33], etc. The applications of satellite formation flying have also extended from deep space exploration to planetary orbit [34].

Coordination in a short distance is the fundamental feature of satellite formation flying. A formation mission requires satellites to maintain a particular geometry and relative motion relationship. However, the dynamic characteristics of a satellite orbit and complex attitude coordination tasks determine that the relationship between them is time varying, and the presence of interference leads to uncertainties of the variation. Therefore, the key problem of cooperative control with high precision must be solved in satellite formation flying [35]. For special tasks, such as synthetic aperture imaging and optical astronomy observation, the relative state determination and shape keeping control in a millimeter scale or even higher precision are required [36].

The architecture of satellite formation coordination should consider the logical and physical information relation and control relation between satellite members and the distribution model of problem solving ability [37]. It is the basis of cooperative behavior of satellite formation, and determines the overall behavior and operational efficiency of satellites. The architecture of satellite formation

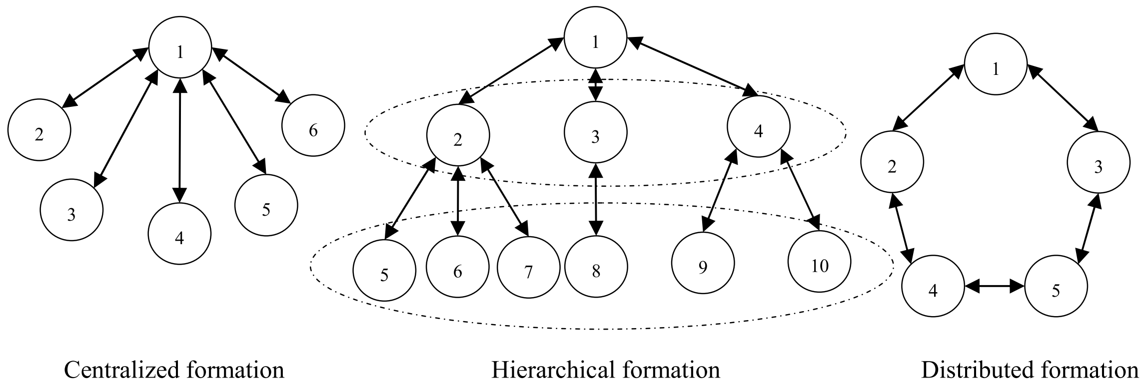

Fig. 1. ***The architecture of satellite formation coordination.***

coordination can be divided into centralized and decentralized systems in general, and also the decentralized structure can be subdivided into hierarchical and distributed ones, as shown in Fig. 1. The comparison of satellite formation coordination architectures is given in Table 1.

In terms of different structures, formation control methods can be classified as the leader following method, the behavior-based method, the virtual structure method, the cyclic pursuit method, the artificial potential function method, the algebraic graph method, etc. [38]. At present, these formation control methods have gradually been mixed together and are difficultly separated. In particular, the algebraic graph method has attracted much attention of researchers in recent years since the mature graph theory can be used for studying formation control design, formation configuration, formation information flow, etc. Several other methods have also been integrated and become a mainstream method of formation control.

The object and dynamic environment of satellite coordinative control, and the configuration of sensors and actuators affect the formation cooperative control design. In light of control objects, the coordinative control of satellite formation can be categorized into coordinative attitude control, coordinative position control, and coordinative coupled attitude-orbit control. Because of the coupling relationship between the attitude and orbit control of satellites, the actual satellite formation mission separates coordinative attitude control and coordinative position control. When designing them separately, the coupling relationship between the attitude and position is neglected, which results in low control accuracy of a formation system. In order to improve the attitude and position control accuracy of a formation system, more and more attention has been paid to the coordinative coupled attitude-orbit control [39].

Table 1 Comparison of Satellite Formation Coordination Architectures

	Advantages	Disadvantages
Centralized formation	Good global superiority	Poor reliability and scalability
Hierarchical formation	High reliability and scalability Little communication traffic	Local information only
Decentralized formation	Good flexibility of structure	Low reliability

In addition to the control algorithms, space environment, measurement sensors, and actuators of satellite members, the overall controllability of satellite formation is also affected by information interaction, such as intersatellite communication and relative state determination. Due to the complexity of the space environment, the bidirectional communication between satellite members sometimes cannot be realized, and the information interaction between neighboring satellites can only be achieved by directional communication. This implies that the control algorithm is not only applicable to the satellite members with a topological structure as undirected graph, but also is applicable to the satellite members with a topological structure as directed graph. To reduce costs or under the condition of failure, satellite-borne sensors are limited and cannot provide full state information, which requires that the cooperative control algorithm be applicable not only to the condition that all the states of the formation system are measurable, but also to the condition that only a part of the states can be measured. Due to the physical constraints of actuators, the control force and torque provided by satellites have certain upper bounds, which needs the consideration of actuator saturation when employing control strategies. It is required that a number of satellites act simultaneously to generate desired control performance with characteristics of attitude and orbit coupling [40].

III. DISTRIBUTED SATELLITE SYSTEMS

As a new type of distributed space systems, the coordinative control system of satellite formation has attracted the attention of world's major countries. Since the 1990s, the U.S. National Aeronautics and Space Administration (NASA) and the U.S. Air Force Research Laboratory, the European Space Agency (ESA), the German Space Center, and other research institutions and countries have to solve the problem of a large number of scientific experiments and demonstration verification projects [41]–[44]. The successful launch of TerraSAR-X satellite in 2007 and TanDEM-X satellite in 2010 by the German Aerospace Center (DLR) and EADS Astrium (now Airbus Defence and Space) for twin satellite formation, which were controlled with typical distances between 250 and 500 m, made great research progress and important achievements in technology, a preliminary validation of the technical advantages and applications of satellite formation flying [45]. China launched the satellite Shi Jian-9 (SJ-9A) in 2012 completing the formation flying test of satellites and high-precision test of GPS inter satellite measurement, verifying the establish and maintenance technology of satellite formation [46]. A number of programs on distributed satellite systems have been proposed in recent years.

In 1996, "Air Force Operation Plan 2025" proposed by the U.S. Air Force pointed out that a distributed system being composed of small satellites is the main means to provide real-time information services for continuous operation, and effective anti-satellite weapons. Inspired by the formation of flying birds, the scientists of the U.S. Air Force Research Laboratory launched the concept of the satellite network formation, and developed the Technology Satellite of the 21st Century (Techsat-21) program. This is a revolutionary distributed satellite system, which can adapt to rapidly changing mission requirements. From the beginning of 1998, the U.S. Air Force began to launch multiple satellites Techsat-21, each of which weighs 70 kg, into the orbit. They expanded from the flat structure to the cylindrical one, kept a distance between 200 and 500 m from each other, and constituted a distributed surveillance satellite group. The planned space-based radar system includes 40 groups of small satellites. Each group has eight satellites, each satellite weighs about 100 kg, the entire cost of the system is only one-third of the similar system, and the performance will be three times better. Since 2000, the U.S. Air Force also carried out Techsat-21 joint flight experiments in the orbit of 600 km to verify the satellite formation concept. Although it made some achievements in the whole system and formation flying since the plan was proposed, it faced many technical and financial problems. So, the flight test was repeatedly postponed and the project was finally canceled in 2003 due to numerous cost overruns. However, as the program has integrated almost all key technologies of the distributed satellite system, it was the focus of attention [47].

The ESA Cluster II plan also attracted attention of the international space community. Cluster II consists of four identical satellites that fly in a tetrahedral formation and is a constellation Earth space exploration program to complete a task of unprecedented scale space ESA detection [48]. Those four satellites were successfully launched in pairs by Soyuz-Fregat rockets from Baikonur in Kazakhstan. The first batch of two Cluster II satellites Salsa and Samba was successfully launched on July 16, 2000 and the second installment of the launch of the two Cluster II satellites Rmba and Tango was launched on August 9, 2000. In five days after the launch of the second batch of satellites, the four satellites were joined with each other, according to the scheduled plan for the formation. After three months of orbit adjustment and instrument data checking, the Cluster II detection mission was formally implemented. The self-inspection system of the four satellites showed that the satellite system worked properly. Originally planned to last until the end of 2003, Cluster II mission has been extended several times and is now extended until the end of 2018. Additionally, the China National Space Administration/ESA Double Star mission operated alongside Cluster II from 2004 to 2007 [49].

The PROBA-3 mission is the third satellite mission in the ESA's series of PROBA low-cost satellites to validate new spacecraft technologies. The new activities submitted at the ESA ministerial meeting in December 2005 included the design, research, and development of a group of small satellites, and the full scale tests and validations of formation flying missions in orbit. PROBA-3 will verify technologies required for multiple satellite formation flying. On the two PROBA-3 satellites for formation flying tasks, the preliminary design of the smaller one needs to develop special technologies, which are beyond the cutting-edge technologies of current measurement, satellite guidance, navigation, and control in the field. PROBA-3 (currently in the preresearch stage) consists of two independent three-axis stabilized satellites that can fly closely to one another with precise attitude control capabilities and keep a distance of 150 m between the two satellites. PROBA-3 satellites are expected to launch in 2020 [50].

In order to accumulate the necessary technical support for applications of distributed satellites, the Defense Advanced Research Projects Agency (DARPA) issued the System F6 program in 2007, which aims to prove the feasibility and benefits of the distributed satellite architecture with the features of the Future, Fast, Flexible, Fractionated, Free-Flying (F6) satellite flight [51]. The F6 satellites refer to fractionated formation flying satellites, used to explore the construction of the distributed satellite architecture. The architecture will divide the traditional single satellite into several functional modules. Each module employs wireless networks for data transmission and distributed computing and all the modules through the virtual satellite formation flying in orbit carry out space missions, which could effectively reduce the risk that traditional single satellites face. The goal of System F6 is to develop and demonstrate a new space structure of the satellite group. In this new type of space structures, a traditional large multifunctional satellite is replaced by a networked satellite cluster. The advantages of such a satellite cluster are overall risk reduction, more flexible budget, faster initial deployment, and enhanced survivability. In the design, manufacture, and operation of space systems, System F6 becomes a revolutionary technological innovation. It is not only a technological improvement, but also the fundamental change in the entire space sector. The modularization and network structure in System F6 can solve the problems of increasing cost, delay in delivery, launch accident and orbit failure. System F6 is likely to be a landmark event in the history of military space systems, as well as the revolutionary change of the Internet to data communications. System F6 presents a spatial unprecedented flexibility and robustness concept.

In addition, there are a number of other networked small satellite projects [52]–[55]. For example, the U.S. Air Force laboratory, the National Defense Advanced Research Projects Agency, and the Department of Aeronautics and Astronautics in the United States jointly proposed the university nanosatllite program to verify the formation flying technology. The Orion microsatellite project supported by the U.S. space agency is to achieve the formation of flight and the concept of a virtual space platform via several key science and technology experiments. NASA supports a new millennium program with a total of more than 30 space projects to validate distributed satellite technologies with demonstration. In addition to the United States, Europe and other countries have also developed and implemented a number of space programs for multisatellite coordinative control systems, for example, the ESA Infrared Space Interferometry Mission—Darwin [56], the ESA's Laser Interferometer Space Antenna (LISA) mission [57], and the French Space Agency interferometric cartwheel [58].

In recent years, the research on coordinative control systems of satellite formation in China has been developed rapidly. At the Xiangshan Science Conference in 2003, Chinese aerospace experts from various fields discussed space formation and space virtual detection technology to explore how China develops technology of satellite formation flight, space virtual detection, distributed synthetic aperture radar and modern small satellites, and other cutting-edge technology. It was to seek a road of low cost, fast speed, high efficiency, and high reliability, based on the actual situation of China's space [59]. Moreover, in 2004 and 2008, the Harbin Institute of Technology developed Experimental Satellite 1 and Experimental Satellite 3 that were launched successfully, which indicates that China made an important step in the field of distributed satellites. In 2006, the experiments of the double satellite formation flight were carried out on the microsatellite Tsinghua-1 developed by Tsinghua University and the nanosatellite SNAP-1 developed with the British Surrey Satellite Technology. The above work implies that China is in the initial stage of the research on the networked satellite formation.

IV. FRACTIONATED SATELLITE FORMATION

The concept of fractionated satellites is a new milestone in the development of satellites and has attracted the attention of the major space powers in the world which have developed and implemented flying plans of their own fractionated satellite formation. The idea of fractionated satellites dates back to an article by Molette in 1984 [60], then attracted the U.S. military's attention, and has become a research hotspot in the field of aerospace in recent years. At the fourth responsive space conference in April 2006, Brown and Eremenko in a joint paper pointed out that a fractionated spacecraft offers more flexibility and robustness than traditional satellites during mission operations, design, and procurement [61]. The fractionated satellite is the implementation of better responsive space, and extended the connotation of networking and formation as the representative of the small satellite group to an application pattern of cluster satellites. A fractioned satellite consists of various function modules according to the decomposition functions for satellite payload, power, energy, communication, and so on. Those modules are launched individually and each module of physical separation is operated through wireless data links and wireless energy transmission in orbit. The virtual satellite constitutes a complete function of a traditional satellite to accomplish a specific task, which has the ability of function, redefinition, and system reconstruction. A satellite cluster is made up of different function modules with independent structure and physical separation. Through the realization of a single or a plurality of the satellite self-organizing network and cluster flight mode, it has the ability for quick assembly, fast launch, rapid deployment and application, multimode information features, and fusion. The independent maintenance, replacement, upgrade, and reconstruction of fractionated satellite formation are key satellite technologies. This is an important direction for the development of satellite clusters.

A fractionated satellite formation has the following advantages: 1) it shortens the satellite development time and reduces the launch cost and risk; 2) it can be equipped with different task loads; 3) it enhances system scalability and reconstruction ability; and 4) it enriches new test technologies and novel load space development methods. Based on those advantages above, DARPA officially decided to develop a fractionated satellite system as a research and development project in 2007, named System F6 [51]. System F6 aims to design fractionated satellites by breaking the traditional integrated satellite structure, build a cluster satellite system with features of function decomposition, structure separation, wireless connection, and formation flight, and validate wireless data connection and wireless energy transmission technology in orbit. The key technologies include modular technology, wireless transmission technology, formation flying control technology, network technology, and distributed computing technology.

System F6 is different from a traditional satellite formation flying system in the physical structure in two aspects. One is that each formation member is not a complete satellite, but a part of a satellite (one or some functional modules), and specific missions are jointly completed by all the functional modules. The other is that the characteristic function modules are standardized and generalized so that the modules are easy to change, expand, or upgrade. Therefore, System F6 is essentially a heterogeneous distributed satellite system, which means each fractionated satellite often has a different configuration. System F6 is implemented in four phases. In the first phase, the concept of the system and the design of the project frame are verified. The second phase of the system completes the design and development of practical hardware. In the third phase, the design, manufacture, and experiments of a small satellite group are accomplished. The fourth phase launches a small satellite group for demonstration. In 2008, the U.S. DARPA signed the contracts for the first phase task with Boeing, Lockheed Martin, Northrop Grumman, and Orbital Sciences [62]. DARPA awarded the second phase of the program to Orbital Sciences along with IBM and Jet Propulsion Laboratory (JPL) in 2009 [63]. Flight demonstration verification was expected in 2013. But, in that year, DARPA confirmed that they canceled the Formation-flying Satellite Demo, which means that System F6 project was terminated [64].

Compared with the traditional system of monolithic satellite formation flying, the coordinative control of attitudes and positions of fractioned satellites is consistent, but the control accuracy is not high to maintain a certain formation, usually just to satisfy the wireless energy transmission and information exchange requirements. However, there exist the following particulars in the control of satellite attitudes and positions. 1) The partial states of the modules are immeasurable. To ensure the single fractioned satellite volume is minimized, each module has only a part of function of the satellite and some devices are not equipped, e.g., some speed measuring devices may not be configured in a module so that the angular velocity or velocity of relative motion information is not available. 2) The response speed and tracking ability of the attitude and position control of each module is different. This is mainly due to the various modules with different inertia and mass. 3) To realize some special flight tasks, such as the rendezvous, docking, and orbit assembly of different functional modules, it is necessary to coordinate the attitude and position at the same time with six degrees of freedom (6-DOF). These problems raise a challenge to the coordinative control of fractioned satellite attitudes and positions.

V. LEADER-FOLLOWING FORMATION CONTROL OF SATELLITES

The leader-following formation control of satellites refers to the fact that some satellite members serve as leaders, while others act as followers, the followers track the trajectory of the leaders to achieve formation control, and the formation control problem is transformed into a single satellite control problem of followers tracking the position and attitude of the leaders. A variety of forms of implementation, as shown in Fig. 2, are achieved, for example, the single-leader structure, multileader structure, virtual-leader structure, etc. [65].

The control tasks of satellite formation consist of relative orbit control and relative attitude control of satellites. The relative orbit control includes formation initialization, formation reconfiguration, and formation maintenance. The formation reconfiguration is different from the orbit transition of a single satellite, which not only requires each satellite to complete the corresponding orbit transfer, but also requires coordinative movement of formation satellites. The early formation reconfiguration was studied by applying the theory of optimal control and the principle of permutation and combination to design the formation reconfiguration strategy for deep space free-flying satellites [66]. The formation initialization can be regarded as a typical formation reconfiguration. For the formation initialization and formation reconfiguration, the tasks with low control accuracy and short control time are mostly implemented by impulse thrust. Based on the Gauss perturbation equation, the pulse setting strategy was presented for satellite formation under the influence of J2 perturbation [67] and an initialization strategy was designed for a general reference orbit [68].

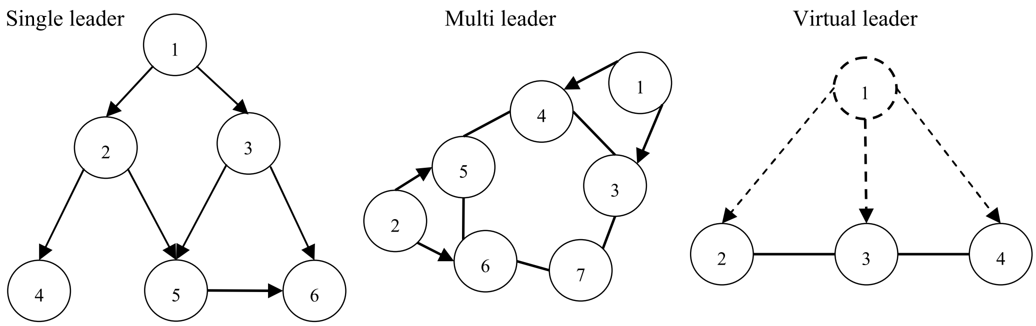

Fig. 2. ***Leader-following formation.***

In addition to the relative position of satellite formation that should meet certain conditions, its relative attitude should also maintain a certain regularity of coordination to ensure information sharing of the whole formation, and jointly complete some complex tasks. The leader-following control method was adopted for design of the attitude cooperative tracking control algorithm based on quaternion and MRP, respectively. Subsequently, much work has been carried out on attitude coordination, such as interference, model uncertainty, self-adaptation, actuator saturation, etc. [69]–[73]. Due to cost reduction or faults, there may be a gyro-free configuration scheme and the attitude angular velocity measurement information cannot be obtained. By constructing a nonlinear angular velocity estimator, an output feedback tracking controller and an output feedback synchronization controller were designed without angular velocity measurement for master satellites and slave satellites, respectively [74].

VI. BEHAVIOR-BASED FORMATION CONTROL OF SATELLITES

The idea of the behavior-based formation control of satellites is to specify multiple expected behaviors for each control event in the overall system, such as collision avoidance, formation reconfiguration, formation keeping, target tracking, etc. Each behavior has its own purpose or task. Through the design of the basic behaviors of satellite members and local control rules, the overall behavior required of the satellite formation is achieved, in which the key problem is to design basic behaviors and effective behavior coordination mechanisms (i.e., behavior choice problems) [75]. The behavior-based formation method was applied to satellite formation coordinative control to realize the annular configuration maintenance of uniform distribution of Earth orbit [76], and avoid the collision between satellites. Also, the behavior-based formation approach was employed to the cluster cooperative tasks of deep space exploration satellites [77]. At the individual level, four simple behaviors were defined as: avoid collision, remain grouped, align to the neighbor, and reach a goal. Based on individual celestial mechanics and other certain knowledge, the desired global behavior was formed through the interaction of four behavioral rules. It concluded that if the individual behavior can be accurately executed, the method can effectively implement cluster independent management without centralized global control.

The behavior-based formation strategy is mainly used to deal with conflicting requirements, while it is less used for communication interaction between satellites. It has a good adaptability to systems with multiple interaction effects, especially for large-scale satellite formation. However, it is hard to design the local basic behavior and local control planning for specified formation, and the stability of formation control is not guaranteed. The core idea of the null-space-based (NSB) behavioral approach is to treat multiagent systems as a whole constrained system and define each basic behavior [78]. Based on the NSB behavioral control strategy and aiming at two stable and mutually conflicting tasks, i.e., obstacle avoidance and formation reconfiguration, the NSB kinematic equation based on a relative displacement model was derived, and a passive sliding mode control algorithm was designed, which makes the closed-loop system achieve global exponential stability [79].

VII. VIRTUAL STRUCTURE FORMATION CONTROL OF SATELLITES

The virtual structure formation method was introduced in multirobot coordination problems [80]. The idea of virtual structure formation control is to treat the whole system as a single class of rigid body structures and to conduct entire control or maneuver, as shown in Fig. 3. The relative geometry relationship between individuals is maintained, and the position and attitude of desired formation and tracking are realized. To apply the virtual structure formation method, the desired dynamics of the virtual structure needs to be defined. Then, according to the local or global information, the desired state of each satellite can be obtained, and single satellite tracking control is used to track a reference trajectory.

The virtual structure formation method can easily specify formation behaviors without an explicit leader, and the formation error can be introduced into the design of the control law as feedback to achieve higher control precision. Since the virtual structure formation method does not rely on a single real unit, it has higher robustness than the leader-following formation method. It has been widely used in the problem on formation coordination in autonomous robots [81], [82], unmanned aerial vehicles [83], and underwater vehicles [84].

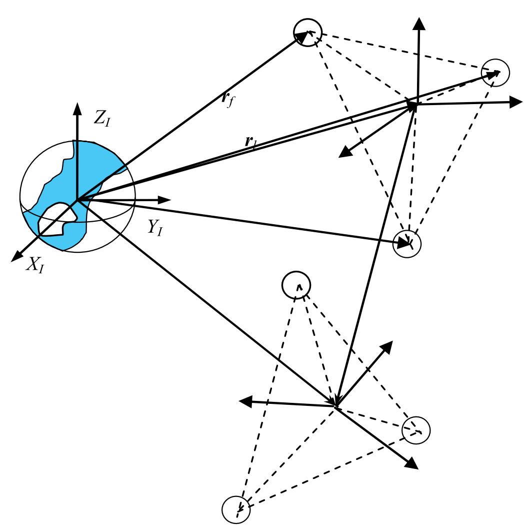

Fig. 3. ***Virtual structure formation.***

Aiming at the formation mission of deep space interference imaging, a virtual structure formation method was introduced to design a three-layer formation coordination framework, which has a dynamic transfer layer between subtasks, a satellite member motion coordination layer, and a satellite member control layer [85]. The information feedback between three layers was added to improve the stability of the system. The aforementioned virtual structure is essentially centralized, which can lead to the single point of failure existing in any centralized implementation. A distributed virtual structure formation architecture was further proposed, in which each satellite member adopts a parallel cooperative mode to avoid the appearance of a master satellite in the loop, improving flexibility, reliability, and robustness of the system [86].

A decentralized control algorithm was proposed, which regards the leader as the reference point of each formation member, and uses two aggregation behaviors (cohesion and repulsion) to achieve local position control [87]. Inspired by the fact that the shepherd is able to take care of the whole flock by controlling the sheep on the border, a method was presented to control the shape of time-varying formation by selecting individuals as coleaders on the boundary [88].

VIII. CYCLIC PURSUIT FORMATION CONTROL OF SATELLITES

The cyclic pursuit formation method is abstracted from the behavior of biological individuals tracking each other and originates from the mathematical problem of tracking curve. This method is similar to the traditional leader-following strategy, but the leader which the individuals follow is different. With many individuals tracking back and forth, and end to end, the method essentially adopts bidirectional or unidirectional ring graph topology of information interaction. The cyclic pursuit formation method is a type of distributed cooperative control, as shown in Fig. 4.

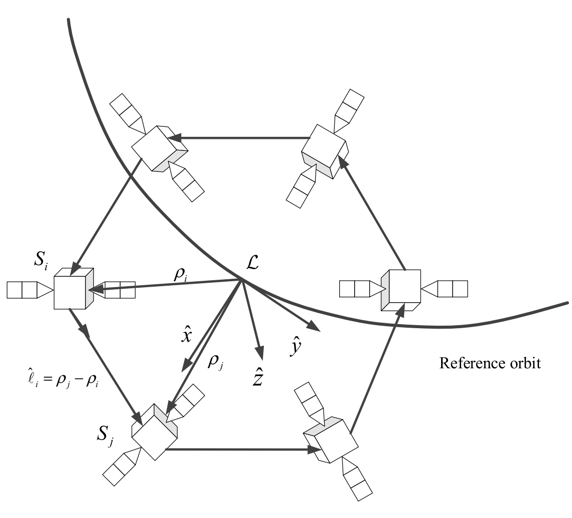

Fig. 4. *Cyclic pursuit formation.*

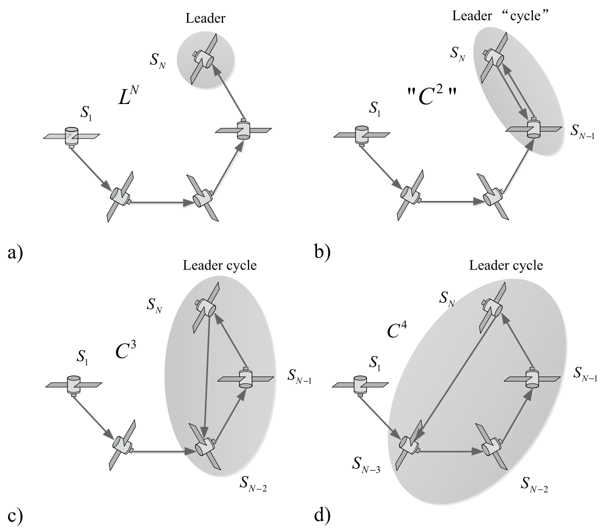

Fig. 5. *Leadership variation of cyclic pursuit formation [92].*

By allowing nonhierarchical connection between individuals, the control capability can be distributed more evenly, and the control goal of the whole system can be achieved only by relying on local measurement information [89].

The cyclic pursuit formation method has many advantages. For example, the relative measurement that includes only position and speed can effectively reduce information interaction, i.e., it needs only minimum communication connections. There is no fixed leader satellite so that it has strong anti-interference performance, as shown in Fig. 5. Moreover, a local control gain can be adjusted to achieve global convergence. The aforementioned conventional cyclic pursuit formation method is based on the particle model assumption, and the speed direction of the tracker is directed to the tracked target in real time, which is a class of linear cyclic pursuit algorithm. In actual formation control, due to the limit of controlled execution and time lag effect, a nonlinear cyclic pursuit method has received much attention [90], [91].

The cyclic pursuit formation method was introduced into satellite formation coordination and utilized for formation keeping control of satellites using measurement based on line of sight [92]. An open–close cyclic pursuit strategy was proposed by introducing a rotating coupling matrix to allow each satellite control input bias by a rotation angle so that the desired geometric satellite formation configuration and the control law with decentralized coordination and symmetrical characteristics can be easily obtained [93]. A cyclic pursuit controller was designed for formation configuration of symmetric satellites and the stability and convergence of a control algorithm was analyzed using the contraction theory. The feasibility of extending it to EMFF was preliminarily discussed and verified by experiments.

IX. FORMATION CONTROL OF SATELLITES USING ARTIFICIAL POTENTIAL FUNCTIONS

Artificial potential functions originating from the concept of potential energy in physics are widely used in the design of control laws or guidance laws for various nonlinear motion systems. Formation control of satellites using artificial potential functions considers the motion of a satellite in the space as the motion in a virtual potential field. The target satellite generates gravity and obstacles or other close satellites create repulsion so that the gravitational force and repulsion force generate a potential function. In the potential field, a satellite moves around colliding object and goes toward the target due to abstract forces. The artificial potential function method has the advantages of simple calculation and easy realization of real-time control. Its disadvantage is that there are local extreme points and the design of a potential function is hard.

The artificial potential function can be used to describe target tracking, configuration preservation, collision avoidance, obstacle avoidance, etc., and the composite control target consisting of the above actions. It was first used for path planning in a satellite formation system, which is the basis of collision free navigation. The formation path planning using artificial potential functions was proposed, which was validated to be a simple and efficient path planning algorithm for obstacle avoidance and collision avoidance [94]. A sensitive constrained satellite formation path planning method was presented, based on a behavioral framework, to coordinate the responses of satellite members so as to achieve a common mission [95]. Aiming at autonomous maneuvering tasks, a guidance method utilizing artificial potential functions was studied to implement complex maneuvering real-time control calculation in orbit [96]. The potential functions were employed to achieve the autonomous maintenance of the planar constellation phase configuration [97].

X. FORMATION CONTROL OF SATELLITES USING ALGEBRAIC GRAPH

The algebraic graph formation method means the formation structure is represented in terms of the structure of various graphs, analysis, and control based on graphs, as shown in Fig. 6. As a natural description of networked systems, the algebraic graph theory depicts a network system in which vertices represent network nodes and edges denote information interactions between network nodes. The algebraic graph theory provides algebraic descriptions of many network topologies (such as Laplace matrix, adjacency matrix, incidence matrix, etc.). These algebraic descriptions can not only visually and interactively describe the intersatellite information interaction mode, but also facilitate the study of the influence of information interaction among system members on the whole system. So, the algebraic graph theory is a new powerful mathematical tool for the study of cooperative control of large-scale satellite formation with information constraints [98], [99].

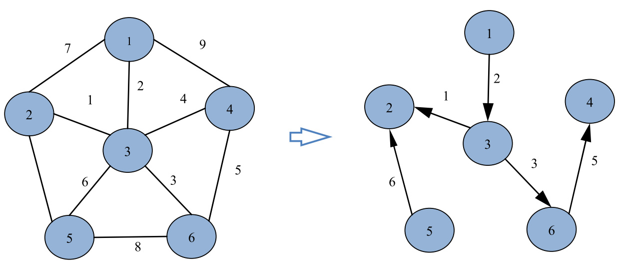

Fig. 6. *Algebraic graph formation.*

The communication topology plays an important role in the astringency of satellite formation. Limited by relative measurement, such as the field of view of sensors and the range of communication, and the influence of mutual occlusion between satellites, it is hard to realize one-to-one relative measurement or intersatellite communication among members of multisatellite formation, and the information sharing network is generally unidirectional and sparse topology. Moreover, affected by the position and attitude of satellites, the access or exit of new and old satellites, and the error code or packet loss in intersatellite communication, the actual information sharing link may also have the phenomenon of short interruption, loss, or reconstruction, and the formation information topology presents time-varying characteristics. Much research work has been carried out on communication topology switching [100], communication delays [101], time-varying delays of communication [102], uncertainties [103], and so on. Except for communication modes (undirected graphs and directed graphs), it is also affected by external disturbances, the limitation of measurement devices, the delays and switching in communication links, the uncertainties of the internal parameters of a system, and the physical constraints of actuators. The formation control of large deep space satellites is studied under the switching topology.

XI. FORMATION CONTROL OF SATELLITES USING NON-CONTACT FORCES

The traditional satellite formation controls the relative motion of satellites mainly by thrusters that consume a certain amount of propellant, which limits the ability and life of satellite formation flying. It is an effective way to control the relative motion of satellites by the use of the interaction force between satellites. Currently, the research work mainly focuses on two aspects: the contact force between satellites represented by tether and noncontact internal force between satellites represented by the electromagnetic force between satellites, Coulomb force, Flux-pinned effect force, and so on [104], [105]. The force produced by the interaction of electric or magnetic fields between satellites can not only effectively avoid the inherent weakness of a thruster, but also has the advantages of noncontact, continuous, reversible, and synchronous control, which provides a novel idea and approach for satellite formation control.

Kong *et al.* [106] first proposed the concept of electromagnetic formation flying. By installing electromagnetic coils in the satellites of formation, the electromagnetic formation controls the relative motion of the satellites by coupling electromagnetic force/torque between the satellites, produced by the interaction of a magnetic field after energizing to meet specific needs of formation. Compared with other noncontact internal forces between satellites, the electromagnetic force can provide any direction of gravitational/repulsive interaction and can control the relative position and attitude of satellites at the same time, which is not limited by orbit factors. It has better control ability and more universal applications

Besides the satellite formation using electromagnetic forces, Coulomb force formation, Flux-pinned effect force formation, etc., also appeared. In the Coulomb force formation proposed by King *et al.* [107], a satellite can control the power of its surface by active injection of negative charge (electrons) or positive charge (ions), and then produce electrostatic repulsion or attraction between satellites to realize relative position control of satellites. The current research work mainly focuses on Coulomb force modeling, formation dynamics and stability, typical configuration analysis, and formation maintenance and reconstruction [108]. In addition to conventional formation missions, extensive applications of Coulomb forces are worth attention, including debris-assisted deorbit [109], space assembling [110], and auxiliary orbit correction [111]. The Flux-pinned effect force is produced by the interaction between a high temperature superconductor and a permanent magnet, and represents the passive and stable connection of the relative position/attitude between them [112]. If this concept is applied to relative motion of satellites, close range state maintenance, on-orbit docking, and space assembling tasks can be achieved.

Since the satellite's mass center cannot be moved under noncontact internal forces between satellites, its orbit applications are limited. Using hybrid thrust is a necessary choice for a formation system to maneuver in orbit, and can effectively extend its ability to perform space missions. To solve this problem, trajectory planning and configuration control of Coulomb forces combined with ES mechanism was investigated [113].

XII. COORDINATIVE CONTROL OF SATELLITE FORMATION

The coordinative control of satellite formation is one of the key technologies of satellite formation flying. It has been a hot and difficult issue in the field of space control in recent years. For the multisatellite formation configuration, the coordination problem between satellites must be considered at the initial stage. Recently, a hierarchal coordination scheme for satellite formation initialization was proposed, which provides a basis for the study of coordinative control [114]. In the study of coordinative control of the TechSat21 task, an optimal coordinative control method for constrained trajectory generation for microsatellite formation flying was presented to maintain initialization and reconstruct overall optimization with formation ground projection area and communication distance constraints [115]. It integrates the path optimization and control of the satellites into one set to achieve the objective of minimizing fuel consumption. Orbit target tracking and inspection was studied through coordinative control of satellite formation [116]. Some researchers applied convex optimization techniques and linear programming techniques to study the coordinative control and configuration transformation of distributed satellite systems [117]. The linear–quadratic regulator (LQR) control technique was used to study formation keeping for satellites in a circular orbit [118]. Using the ground projected circle orbit configuration as a research object, the discrete time LQR control method was employed to estimate J2 perturbation of the nonspherical Earth under the influence of the configuration required to maintain energy, which was simulated using a high precision model, and the simulation results showed that the energy consumption control is related to the control pulse frequency [119]. For the formation of UoSat-12 and UoSat-2 satellites designed and built by Surrey Satellite Technology Ltd., the LQR feedback control of J2 perturbation was studied [120]. Based on the linearization error of Hill equations and the circular orbit assumption error, a nonlinear output feedback control law was designed using the Lyapunov method to make multiple satellites track their nominal trajectories under the condition of unknown model parameters [121]. With high precision orbit dynamics equation describing the relative motion of satellite formation, an adaptive nonlinear control method and the Lyapunov stability theory were utilized to make tracking range greatly asymptotically stable in perturbation effects and model parameter uncertainties [122]. The sliding mode variable structure control method was investigated to solve the nonlinear tracking control problem of satellite formation with model parameter uncertainties [123]. The phase plane method and the fuzzy control method were applied to the coplane formation maintenance of satellite formation flying [124].

The application of graph theory has been a new idea in the research of formation control of satellites in recent years. For the TPI deep space mission, the controllability problem of the system dynamic communication topology related to the satellite formation states was put forward. Using the polar diagram theory, the existence of a set of control series was studied to obtain an arbitrary expectation communication topology sequence [125]. The information theory was utilized to design a scheduling strategy of AFF sensors, maximize the information or knowledge of satellite formation, and design switching logic of relative perception systems under the constraints of single range or azimuth sensors [126]. For the problem of a deep space interferometer mission formation rotating around a fixed axis, state and output feedback control methods were employed with characteristic axis decomposition rate, but the control stability requires that the inter satellite information flow must be bidirectional in the ring topology and the initial value of the formation needs to meet specific conditions [127]. For the same interferometer task, the rotation control problem of networked rigid bodies spinning around a rigid short axis or an unstable intermediate shaft was considered for satellite formation. The model reduction method and the energy shaping method with integration of a potential function model were applied to design the controller and prove the stability of a formation system if the information topology is undirected [128].

The consensus of satellite formation with coordinative control has been taken into account in recent years. The synchronization algorithm of the attitude rates of a networked rigid body was developed by employing the energy dissipation method, though the explicit solution for the case of a fixed axis was not given [129]. For the consensus problem of networked Euler–Lagrange systems, a consensus algorithm with asymptotic stability was designed under the condition of a connected undirected graph [130]. Furthermore, the actuator saturation problem and the feedback coordinative control problem with unknown differential outputs were studied.

XIII. COORDINATIVE ATTITUDE CONTROL OF SATELLITE FORMATION

Much research on the attitude control of satellite formation has been carried out and many significant achievements on the coordinative attitude control of satellite formation have been made recently. The attitude coordination problem of the deep space interferometer was studied in [131]. The proposed coordinative controller reflects the behavior control and consensus theory, which can ensure the consensus of the overall attitude maneuver for the formation members of the interferometer. In the case that the desired attitude rates is changed, a coordinative controller was designed, including the absolute attitude tracking and the attitude consensus preserving [132]. It is suitable for satellite formation with a general undirected communication topology. Using the consensus theory, the corresponding coordination algorithms were presented for the attitude control problem of a deep space satellite formation [133], [134]. The coordinative attitude controller was designed when the desired signal is known by only a part of the formation members, and the communication topology is extended from undirected graph to directed graph. In terms of a passive design method, a coordinative attitude controller was developed for the attitude consensus maintenance and the attitude rates tracking in a multirigid body motion [135]. Using the Euler–Largarange-based attitude control model with the modified Rodrigo's parameters, a robust attitude controller was presented in [136]. An adaptive robust controller was employed to estimate the bounds of unknown parameters and a coordinative attitude control strategy was proposed in the directed communication topology [137]. A virtual system approach was given to solve the problem of attitude synchronization of multisatellites in the presence of an external reference signal and no external reference signal in the case of communication delays [138]. Based on the design of a kind of double valued logic variables, a hybrid coordinative attitude control method was presented to avoid the attitude expansion problem in [139].

For the attitude estimation of the cluster satellite configuration with satellite trackers and/or relative attitude sensors, the observable sufficient conditions for the attitudes of satellite modules were given using graph theory [140]. Especially, if a satellite module can observe some stars or noncollinear stars with the measurement of the link connected to another satellite module with a star tracker, the attitude of this satellite module is observable. For the attitude tracking control problem of satellite formation with time-varying reference states, a decentralized coordinated attitude controller was designed by decentralization of the virtual structure if the intersatellite annular information flow is undirected [141]. The attitude synchronization of satellite formation without a star sensor in an undirected graph was investigated. Furthermore, in view of a parameter linearization assumption, an attitude coordinative controller was designed under the condition that only a part of the satellite reference attitude rates is known [142]. An attitude synchronization output feedback controller of satellites without attitude rates measurement was constructed on the basis of passivity [143]. Furthermore, the attitude synchronization problem with SO(3) manifold was addressed, which only requires to design the input control rate of relative attitude rates [144]. Also, the attitude synchronization problem with communication delays and reference states was discussed. Moreover, there was a concern on the self-synchronization problem of networked rigid bodies using relatively states. A coordinative controller based on energy shaping and relative dissipation, and a coordinative control consensus algorithm based on SO(3) manifold were designed.

Considering control saturation, the coordinative controller without relative angular velocity feedback reduces attitude consensus. A robust attitude controller with a variable structure was designed by considering external disturbances, parameter uncertainties, and transmission delays in [145]. However, in order to ensure the stability of the controller, there are some limits on the coordinative controller parameters, these limits are hard to be verified directly because of the complexity of the coordinative control system, and a variable structure will inevitably lead to system chattering. A robust coordinative attitude control algorithm with input saturation was proposed in [146], which was further extended to the six-degree-of-freedom (6-DOF) coordinative control of attitude-orbit coupling [147]. Due to the existence of intersatellite communication link data loss, time delays and other issues in the attitude control process of distributed satellites, an attitude control method using the predictive control strategy based on an improved model was provided in [148].

XIV. COORDINATIVE COUPLED ATTITUDE AND ORBIT CONTROL OF SATELLITE FORMATION

The relative coupled orbit and attitude control of satellite formation mainly emphasizes the coordinative control from the system and the overall situation so as to avoid the passive situation of caring for this and losing that. There are four feasible coupling control strategies.

1) The coupling constrained control strategy of independent models adopts relative orbit and attitude dynamics models, respectively, to design a relative orbit controller and attitude controller, and the coupling between the relative orbit and attitude is regarded as a coupling constraint [149].
2) The integrated control strategy, based on a coupling model, first establishes the coupling mode of a relative orbit and attitude, and then designs a corresponding relative orbit and attitude controller using various control theories. Corresponding relative orbit and attitude integrated control algorithms were designed, respectively, for multisatellite formation [150].
3) The independent control strategy of decoupling models represents the coupled dynamics model as an independent relative trajectory dynamics model by introducing auxiliary variables or additional coupling constraints. Thus, two subsystem controllers can be designed independently [151].
4) The offline path planning control strategy adopts an offline method to realize path planning through designing the controller into a path planner and a smoothing device, to reduce the NP-hard problem caused by the high order constraint in coupled orbit and attitude control. Offline path planning can solve such constraints, for example, the potential function method, the geometric heuristic method, the stochastic programming method, the bidirectional random tree theory, etc. [152].

To ensure internal consistency and attitude formation constant among the members of satellite formation, a coordinative formation controller and a coordinative attitude controller were developed for the formation maneuver and attitude tracking, respectively, according to the communication flow with a directed graph [153]. The relative motion control model of satellite formation using double integrals is only suitable for deep space exploration and cannot be extended to the planetary orbital environment [154]. But the case of parameter perturbations and external disturbances was not discussed. Based on an attitude control model described by MRPs and a circular reference orbit under the control of relative motion equations, a robust attitude controller and a team coordination controller were designed in an undirected ring communication topology for the cases of parameter perturbations, external disturbances, and communication delays, respectively [155]. The corresponding stability criteria were derived using the contraction theory, but the communication delays were considered to be time invariant, and the attitude tracking error could be bounded but not convergent to zero when the external disturbances change. By introducing a coordination variable containing an adjacent satellite formation tracking error, a 6-DOF asymptotically stable controller was given in [156], which can guarantee that the system tracks a time-varying reference trajectory at the same time, realizes the internal formation, and keeps the posture consistent.

In the presence of system parameter uncertainties and external disturbances, although the coordinative controllers in [157] and [158] were based on the idea of introducing a coordination error variable, the consensus algorithm is also embodied in its structure. However, it is necessary to point out that both [157] and [158] do not consider the existence of an external reference signal, and it is assumed that the external disturbances and the communication delays are constant. With similar models used in [156], which are the attitude control model describing the Euler angles and the double integral model for relative motion description, the corresponding 6-DOF controller was discussed for the cases of system parameter perturbations, external disturbances, no communication time delay, constant time delays, time-varying communication delays, and switching topology, respectively. It expects the attitude and position control systems to achieve time-varying tracking and at the same time to ensure the consensus and invariability of attitude formation. But, it is noted that coordinative controller design in [159] for the case of time-varying communication delays puts a more stringent requirement on delay derivatives that are not greater than zero for the communication delays and the time delays are nonincreasing. Using a nonlinear attitude control model described by MRPs and elliptic reference orbit relative motion equation, a 6-DOF motion model of the Euler–Lagrange form was established. In the undirected communication topology, a 6-DOF robust controller was proposed for various cases, with the corresponding proof of stability [160]. Based on an integrated attitude and orbit model in the form of dual four elements, a 6-DOF coordinated controller with a terminal sliding mode and a leader-following mode was presented with robustness to external disturbances, which makes the system stable in a finite time [161][163]. For the asks of space rendezvous for relative orbit maneuver in intercept, hover, and flying, using the parametric eigenstructure assignment method and the model reference tracking theory, a feedback controller and a feedforward compensator were designed using the perturbation parameter sensitivity function to closed-loop poles as an optimization index [164].

XV. DISCUSSION AND CONCLUSION

The formation control of small satellites is a distributed control problem and its control architecture has a decisive influence on the system performance. The formation control of small satellites has been studied with some preliminary results. This paper has surveyed the recent progress in formation control of small satellites. Various formation control methods and architectures of small satellites have been introduced with achievements. Due to Earth's gravitational perturbation, various uncertainties, interaction among satellites, and other more complex factors in satellite formation, there still exist a number of challenges, such as a large-scale size, high precision performance, efficient coordination, etc.

The scale of satellite formation is increasing with the number of satellites in the formation. From the traditional double-satellite formation and three-satellite formation, it gradually increases to more than ten, to the subsequent dozens, hundreds, or more in recent years. As the large-scale satellite formation is controlled by the communication performance of the system structure and space constraints, it is hard to obtain the real-time formation of the whole state information, which brings difficulties and new problems to the coordinative formation control. For specific control system structures, incomplete information, and limited communication constraints of large-scale satellite formations, more advanced coordinative formation control methods need to be explored to meet the mission requirements of formation control and technology development. The traditional deterministic modeling and control methods have been difficult to adapt to the above changes. In the future, control methods based on graphs and means of randomization will be explored.

Control of satellite formation with ultrahigh precision in the future makes the objectives of satellite formation become higher and higher. The control accuracy is increased day by day for space virtual optical observation formations. Coordinative control accuracy at a micrometer level may be required. Therefore, more accurate modeling, more constraints, and disturbances should be considered, and higher precision control algorithms should be put forward. Networked multiagent control methods, e.g., the networked predictive control method [165], the cloud-computing-based control method [166], will be adopted for precision control of satellite formation.

Future satellites will become smaller and resources more limited. In the premise that the formation target is satisfied, the challenging issue is how to explore new collaboration tools to reduce satellite communication and resource and so on. Advanced collaborative control methods will be implemented, such as quantization control methods and event-driven control methods under the premise of ensuring fleet targets, reducing intersatellite communication requirements, and satellite resource consumption.

For many new satellite formation tasks, such as modular cluster flight, electromagnetic force, Coulomb force formation, and so on, novel coordinative control methods are urgently needed for cooperative targets and intersatellite noncontact force. New cooperative control methods of satellite formation with a distributed execution mechanism will be explored. ■

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ABOUT THE AUTHORS

Guo-Ping Liu (Fellow, IEEE) received the B.Eng. and M.Eng. degrees in automation from the Central South University, Changsha, China, in 1982 and 1985, respectively, and the Ph.D. degree in control engineering from the University of Manchester, Manchester, U.K., in 1992.

He has been a Professor with the University of South Wales, Pontypridd, U.K., since 2004, a Hundred-Talent Program Visiting Professor with the Chinese Academy of Sciences, Beijing, China, since 2001, and a Changjiang Scholar Visiting Professor with the Harbin Institute of Technology, Harbin, China, since 2008. His current research interests include networked multiagent control systems, nonlinear system identification and control, advanced control of industrial systems, and multiobjective optimization and control. He has authored/coauthored over 200 journal papers and ten books on control systems.

Prof. Liu is an Editor-in-Chief of the *International Journal of Automation and Computing* and a Fellow of the Institution of Engineering and Technology (IET).

Shijie Zhang received the B.S., M.S., and Ph.D. degrees in spacecraft design from Harbin Institute of Technology, Harbin, China, in 2000, 2002, and 2005, respectively.

He is currently a Professor of Research Center of Satellite Technology, Harbin Institute of Technology. His primary areas of research are dynamics and control of satellites and formation flying, space mission analysis and design of small satellites. He has been a principal investigator of more than 30 R&D projects related to small satellites, with current projects focusing on orbital and attitude dynamics of small satellites and formation flying, vision-based satellite navigation. He was involved in the development of three small satellites.

Prof. Zhang was a recipient of a Royal Academy of Engineering Research Exchanges with China and India Award - Major Award to study "autonomous control and operation of spacecraft formation using software and hardware technology."