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A REVIEW ON THE DEVELOPMENT OF MICRO-NANO SATELLITE CONSTELLATION AND FORMATION FLYING TECHNOLOGIES

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Abstract: Constellation and formation flying have been becoming the most promising development trends for further micro-nano satellite applications. A review of the development of micro-nano satellite constellation and formation flying technologies is proposed in this paper. The classification, characteristics, and applications of micro-nano satellite constellation and formation flying are illustrated, and the differences between them are argued in details. This paper also provides a brief overview of the advanced technologies and the future development trends of these two kinds of distributed micro-nano satellite system. This work has guiding significance for the research of micro-nano satellite and related fields.

Keywords: micro-nano satellite; constellation; formation flying; networking; distributed satellite system.

Introduction

Micro-nano satellites have taken an increasingly important part in kinds of space missions during recent years. Particularly, distributed micro-nano satellite system has been becoming the most promising development trend for further micro-nano satellite application. The concept of distributed micro-nano satellite system [1] is as follows: by the cooperation of multiple satellites (two or more) distributed in one or more orbits as required, the system can accomplish complex space mission (such as observation, communication, scout, navigation) and realize greater application value. Compared with a single satellite, distributed satellite system may lead the micro-nano satellite to exploit its advantages of miniaturization, high integration and low cost, and offset its disadvantages of simple function, limited resources and short life.

Constellation and formation flying are the most common used distributed micro-nano satellite systems. Because of their great value of application, the micro-nano satellite constellation and formation flying technologies have developed rapidly and been intensively studied. Under the efforts of research institutes all over the world, a number of micro-nano satellite constellations have been deployed and a finite amount of micro-nano satellite formation flying experiments have been conducted. It is the goal of this paper, therefore, to explore the development status, key technologies and future trends of micro-nano satellite constellation and formation flying.

Micro-nano satellite constellation

A micro-nano satellite constellation [2] is a multi-satellite set for completing a specific mission by collaborative working. In general, the satellites of a constellation are distributed in different orbits so that ground coverage area and revisit frequency for a target area will be effectively improved by the cooperation of a quantity of transit satellites. The distributed satellites do not need to maintain a fixed orbit configuration so that the orbit control of each satellite is independent. Accordingly, closed-loop control and information exchange between the satellites are not required.

The following several features are usually used to evaluate the performance of a micro-nano satellite constellation [3]. 1) Coverage performance. For a constellation, the coverage area and the coverage multiplicity are the most important characteristics which decide the coverage quality of a target area. 2) Time resolution. The target area can be covered continuously or intermittently to meet the mission requirements. 3) Economy. The cost of a single satellite, the total number of satellites, the difficulty of deployment and the over-redundancy of system determine the economy of a constellation. 4) Robustness. The functional redundancy, the back-up satellites and the ability of the defective satellites getting off the orbit are the factors to improve the service life of a constellation.

Micro-nano satellites always operate in low orbits, that will provide higher resolution to remote sensing and decrease the communication delay between the satellite and the earth. Therefore, the micro-nano satellite constellation is very suitable for communication and remote sensing. Since 1990s, countries around the world have carried out research and exploration on micro-nano satellite constellation. Most of the deployed constellations provide service for communication and remote sensing, and a few others are navigation satellite constellations or space science experiment satellite constellations. With the development of technology, micro-nano satellite constellations have been extensively used in practical applications. There are some representative examples: the Orbcomm communication satellite constellation is one of the three largest LEO Mobile constellation satellite systems in the United States. From the first launch in 1991, there have been over 70 satellites in orbit to offer service for global short data communications. The Aprize satellite constellation is another communication satellite constellation which was deployed from the year of 2002. It is estimated that there will be 24–64 satellites to provide narrowband data transmission service for mobile and fixed monitoring terminals all over the world when the constellation deployment is complete. The Flock earth observing constellation built and operated by Planet Labs consists of numerous triple CubeSats. It is the largest constellation of earth imaging satellites in the world and it offers the daily global remote sensing data at a resolution of 3–5m. Up to now, over 50 micro-nano satellite constellations in the world have been or are being deployed, becoming a major component of commercial aerospace gradually.

Micro-nano satellite formation flying

A micro-nano satellite formation flying [2] is a series of collaborative satellites which keep a fixed orbit configuration. Members in the satellite formation flying not only have to maintain the formation configuration, but revolve around the earth respectively.

The micro-nano satellite formation flying is equivalent a large virtual satellite, improving the system scale and the measurement baseline incredibly. Closed-loop relative control between member satellites is necessary, and all the satellites need to be coordinated to perform signal processing, communication or functional payload operation together.

The micro-nano satellite formation flying can be distinguished to the following three categories depending on the formation control requirements [4], and both the technical level and the implementation difficulty of them increase gradually. 1) Cooperative formation. The relative measurements and control will be conducted only in a certain mission period instead of long time. 2) Knowledge formation. The formation will obtain the distributed configuration by relative measurements, but the relative control is not required for a lax orbit configuration. 3) Accurate formation. This kind of formation flying requires a strict orbit configuration by means of precise autonomous control and measurements. The relative control and measurement systems result in system coupling, the accurate satellite formation is then formed.

Micro-nano satellite formation flying offers cheaper, more flexible, better performance, and more robust architectures than a single, traditional large satellite. On one hand, larger system scale and measurement baseline will greatly improve the precision of observation. On the other hand, the cooperation, the closed-loop control and the extensive information exchange bring considerable autonomy to the satellite formation flying system, reducing reliance on ground stations. It is obviously that the micro-nano satellite formation flying has enormous potential, however, its practical applications are still limited because of the great difficulty in implementation. AFRL (Air Force Research Laboratory) had ever carried out a grand plan named Techsat-21 since 1998. Several low-cost small satellites flying in formation constitute the Techsat-21 with the performance much better than a traditional large satellite, which will archieve formation flying, on-orbit autonomy, precise time measurement and time service, distributed evacuation aperture radar signal processing, etc. Unfortunately, the plan was forced to be cancelled in 2003 as a result of technical difficulties and budget overruns. 3Csat (3 Corner Sat) formation was developed by three universities in the United States for the demonstration of nano-satellite formation flying and meteorological stereo imaging technology. It is regrettable that in 2004, one of the three satellites failed to catch the launch deadline, and the other two satellites failed to reach the scheduled orbit due to rocket technical problems. ION-F (Ionospheric Observation-Nanosatellite-Formation) was another nano-satellite formation developed by American universities. The primary scientific objective was to measure the fundamental parameters of ionosphereic density irregularities that effect radio wave propagation including communications, navigation, and the GPS (Global Positioning System). The satellites flied as a string of beads, being the first tests of a small satellite formation for making scientific observations of the near Earth space environment. The System F6 (Future, Fast, Flexible, Fractionated, Formation-Flying) project, also called Fractionated Spacecraft, is a satellite architecture where the functional capabilities of a conventional monolithic spacecraft are distributed across multiple modules which interact through wireless links. It is regarded as the technological revolution in the design and development of spacecraft, which was also vigorously promoted by DARPA (Defense Advanced Research Projects Agency). In 2013, DARPA confirmed that they cancelled the Formation-flying Satellite Demo, which meant that they closed the project. As can be seen from the above examples, although the scale and the depth of the technology study increased gradually during past 20 years, the unsolved problems lead the micro-nano satellite formation flying to stay in the stage of theoretical research and flight demonstration.

Key technologies and future development trends

A. High function density micro-nano satellite technology

Function density is the function offered by a unit weight of micro-nano satellite. The higher function density, the more functions and the better performance will be provided by a distributed satellite system. The high function density consists of two levels. 1) The function integration of satellite platform, subsystems, and payloads are high, and they will perform well under the premise of less resources (such as mass, volume, and power) consuming. 2) Percentage of payloads in whole satellite mass is high. The payload ratio is proposed to reach over 60%~70% instead of 30%~40% now. High function density micro-nano satellite technology is based on standardization and modularization of spacecraft design and production technologies, having an important influence on distributed micro-nano satellite system.

B. Satellite networking autonomous operation technology

It is an inevitable trend that the management mode of distributed micro-nano satellite system will turn from the traditional ground station tracking, telemetry and control to the intelligent on-orbit autonomous operation. Fruitful results on single spacecraft on-orbit autonomous operation technology have been achieved during past decades, for instance autonomous spacecraft, autonomous rendezvous and docking, and autonomous attitude and orbit control, laying the foundation for satellite networking autonomous operation technology. The autonomous operation consists of six aspects [5]: 1) coordination and cooperation among satellites; 2) system resource allocation and management; 3) monitoring and handling of abnormal conditions; 4) on-orbit operation mission planning; 5) control command execution; 6) analysis and processing of mission data. The new methods and technologies of satellite networking autonomous operation are in need of being studied and implemented.

C. Inter-satellite relative measurement and control technology

Inter-satellite relative measurements and control technology are the core technologies for distributed satellite system, especially for the formation flying system [6]. On the one hand, the inter-satellite relative measurements include mainly range measurement, azimuth measurement, and relative position measurement. The research into inter-satellite relative measurement technology has been quite thorough, and the methods are generally divided as follows: 1) vision based relative measurement technique; 2) differential relative navigation based on GPS; 3) inter-satellite ranging system. Through certain filtering algorithms, the inter-satellite relative measurement accuracy can be as high as cm level or even μm level. On the other hand, the main tasks of inter-satellite relative control is to capture formation, reconstruct formation and maintain formation. Coupling of three dimensional orbital position and three axis attitude is usually difficult to decouple so that it is a multivariable complex system control problem. Proportional Differential (PD) control method, discrete pulse speed control method, robust control method, and some other methods have been proposed, but the related technologies still need to be further improved.

D. High efficiency orbit control and transfer technology

Applications of micro-nano satellite constellation and formation flying require orbit control and transfer technologies for all aspects of their operations. The application of high efficiency orbit control and transfer technology, also high efficiency micro-propulsion technology, will provide orbital-maneuvering and station-keeping capabilities at possible low cost. Orbit control and transfer technology has been playing an important role throughout the whole space mission of distributed satellite system. In the stage of entering into-orbit, to save the cost of transportation and reduce deployment difficulty, satellites should have the capability of transferring from the drift orbit to the operation orbit by themselves. In the stage of maneuvering control, satellites in the system should implement orbit maneuver according to the mission requirements. In the stage of on-orbit operation and orbit configuration maintenance, station-keeping and relative control capabilities are required. For most micro-nano satellite formation flying missions, orbit control capability is the most important factor limiting their space missions. The most common used micro-propulsion techniques are cold gas propulsion, liquefied gas propulsion, electric propulsion, chemical propulsion, MEMS propulsion, etc. However, none of the existing micro-propulsion techniques is entirely appropriate for the high efficiency orbit control and transfer requirements. A kind of micro-propulsion that can offer high specific impulse, high thrust, high speed increment becomes an imperative requirement.

Conclusions

This paper formulates the concept discrimination between micro-nano satellite constellation and formation flying, and their technical features and characteristics are summarized. Representative examples are listed to illustrate the development status, and key technologies are analyzed to explore the future development trends. This work offers an in-depth analysis of the advanced technology of distributed micro-nano satellite system, having reference significance to researchers in related fields.

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