Survey on Micro-nano Cluster Applications and Its Guidance, Navigation and Control Technology Status

Wanying Gao* and Kehang Li
Science and Technology on Space Intelligent Control Laboratory, Beijing Institute of Control Engineering, Beijing 100190, China

*Corresponding author: 1140410316@stu.hit.edu.cn

Abstract. Nearly 3000 micro-nano satellites have been launched worldwide, and the resulting micro-nano clusters have attracted extensive attention from the international aerospace community. In order to better understand the development level of micro-nano clusters, this paper investigates some typical satellite swarm missions, summarizes the current status of guidance, navigation and control technologies for clusters, and looks forward to the development of China’s micro-nano cluster missions.

Keywords: Micro-nano cluster, micro-nano satellite, cubeSat.

1. Introduction
Micro-nano satellites have high function density, short development cycle, low cost, strong flexibility and expansibility. They can form micro-nano cluster and work together to complete space missions, which meets the development demand of low-cost space system. Micro-nano cluster has become a new research hotspot in the space field.

In recent years, a number of micro-nano cluster missions have been carried out at home and abroad, such as KickSat, Flock, and BlackJack. This paper investigates the application status of these missions, and comprehensively analyzes the development of their guidance, navigation and control (GNC) technology.

2. The Application Status of Micro-nano Cluster
The United States and Europe have entered the application stage in the field of micro-nano cluster. Among the numerous missions that have been carried out, Flock satellites for space remote sensing observation can reach a spatial resolution of 3-5m, and may reach 1 m in the future [1]. The BlackJack program for space-based attack and defense is expected to move into large-scale military applications.

China is still in the initial stage of exploration in the field of micro-nano cluster. Some verification missions of micro-nano satellites have been developed, such as Tiantuo-3. Some micro-nano cluster missions have been planned, but fewer on-orbit tests have been conducted.

2.1. Colony-1
In 2009, National Reconnaissance Office started the Colony-1 Program, and aims to use CubeSat as a space test platform for new technology verification. The mission consists of two 3U CubeSats, which...
were launched into a $275 \times 300$km orbit on December 8, 2010. These two CubeSats was on orbit for more than 30 days, providing experience in the design, launch, and on-orbit operations of CubeSat. Due to the low orbit (300km) atmospheric drag, adjusting the solar panel of the satellite can provide a stabilization torque. Combining the reaction wheels and torque coils, the satellite can be operated in a "Space Dart" mode [2].

2.2. AeroCube
AeroCube is a series of CubeSat technology demonstration missions within the PicoSat Program of The Aerospace Corporation. The AeroCube-4 mission, launched on September 13, 2012, contains three 1U CubeSat operating in a $480 \times 780$km orbit. Each satellite uses GPS receiver to estimate position, and is controlled by opening/closing the solar wings [3].

2.3. KickSat
KickSat is a project to launch many femtosatellites from a 3U CubeSat. Those femtosatellites (Sprites) are chip satellites that weigh about 5 grams. Due to space radiation, the KickSat-1 mission failed in April 2014 [4]. In November 2018, the redesigned KickSat-2 satellite was launched, releasing 105 Sprite satellites. These Sprites successfully established inter-satellite and earth-satellite communication links, then entered the atmosphere as scheduled and burned.

2.4. Flock
The Flock earth observing constellation built and operated by Planet Labs consists of numerous 3U CubeSats. The project aims to provide low-cost commercial earth observation services by using micro-nano satellite networking. Planet Labs has launched a series of Flock since 2014, and the total number of satellites launched has reached more than 300. There are currently about 200 satellites in orbit with a spatial resolution of 3-5m. The Flock satellites have a high rate of revisits and can update data daily to provide the latest information related to climate monitoring, urban planning, disaster response, etc.

Satellites communicate with each other through radio frequency links and use onboard GPS receivers for distance measurement. Since the satellite is too small to have a propulsion system, it can adjust the satellite’s attitude to change the atmospheric drag on the satellite, so as to coordinate the position relationship between the satellites. The Flock-3p’ launched in 2018 are equipped with Field Emission Electric Propulsion.

2.5. Starlink
Starlink is a low-Earth orbit constellation being constructed by SpaceX, providing cheap, high-speed Internet broadband service worldwide. It aims to launch 42,000 small communication satellites.

In February 2018, SpaceX successfully launched two test satellites. In May 2019, it launched the first batch of 60 satellites, completing the first large-scale deployment, then plans to launch a fleet of 60 satellites every two weeks in 2020. Its goal is to provide services in the northern United States and Canada by 2020, then provide near global service by 2021. On October 18, 2020, SpaceX launched the fourteenth batch of satellites. At present, a total of 835 satellites have been launched. In addition to the first batch of satellites launched in 2019, the subsequent satellites all have inter-satellite optical links, enabling inter-satellite networking. In addition, the satellites use Hall-effect thrusters with krypton gas as the reaction mass for orbit raising and station keeping [5].

2.6. BlackJack
To change the current pattern of space that is easy to attack and difficult to defend, In February 2018, the Defense Advanced Research Projects Agency (DARPA) launched the Blackjack program to explore the use of low-cost commercial satellite platforms and rapidly upgradable military payloads to build a low-orbit military communications and reconnaissance satellite constellation. Two test satellites are expected to be launched in 2021, 20 to be deployed by 2022, and eventually develop a constellation of 60-200 satellites.
This project is divided into three phases. At the end of 2018, DARPA has sold platform and payload development contracts to companies. To improve the cluster’s autonomy, the BlackJack project plans to develop an on-board control system called Pit Boss. By November 2019, DARPA has selected three teams to develop Pit Boss.

2.7. **SWIFT**

The Silicon Wafer Integrated Femtosatellites (SWIFT) Swarm Project is proposed by the Jet Propulsion Laboratory, planning to use hundreds or thousands of small femtosatellites to form a micro-nano cluster to obtain complex applications such as sparse aperture measuring instrument. It is planned to use 3D silicon wafer manufacturing and chip-level integration technique to build SWIFT satellite, increasing the component density and reducing satellite size [6].

2.8. **ANTS**

Autonomous Nano-Technology Swarm (ANTS) is an advanced mission concept proposed by the National Aeronautics and Space Administration (NASA), planning to prospect the asteroid belt using 1,000 micro-nano satellites. It is expected to be launched in 2030. The scale of ANTS cluster is large, and the instruments carried by different satellites are not necessarily the same. Through hierarchical management of satellite classification, cluster cooperation and information sharing can be achieved [7].

2.9. **Remove Debris**

European Space Agency (ESA) has been committed to clean up space Debris, it launched a program called Remove Debris, aiming to perform key Active Debris Removal (ADR) technology demonstrations [8]. Using a 100kg satellite to deploy two 2U CubeSat as artificial debris targets in a 400km orbit. Then several key technologies which can be applied to future active debris removal missions are planned to be demonstrated, such as the net experiment, the harpoon target assembly experiment, drag sail, etc.

2.10. **GomX-4**

The Gomx-4 mission, a collaboration between Denmark and ESA, consists of two 6U CubeSat. The two satellites were launched on February 2, 2018 and successfully established an inter-satellite radio connection. During the mission, the two satellites using intersatellite links to worked together and using the Software Defined Radio (SDR) to verify inter-satellite communication technology. Satellite A captures data and sends the data to satellite B through the inter-satellite link. By relying on the differential resistance control of satellite A and the cold gas propulsion system of satellite B, the distance between satellites is kept within the range of 200-4500 km [9].

2.11. **OLFAR**

The Orbiting Low Frequency Antennas for Radio Astronomy Project (OLFAR), launched by the Delft University of Technology, plans to use 50-1000 3U CubeSat to form an orbiting low frequency radio telescope to continuously observe the universe Rays. To avoid radio frequency interference from the earth, OLFAR is planned to be deployed in lunar orbit. After being released into the initial orbit, the satellites drift freely and perform orbital control occasionally to keep inter-satellite distance within 10-100km [10]. The mission is divided into four stages. The first stage is the Netherlands Low Frequency Explorer, which was launched in The Chang’e-4 mission of China in May 2018. The long-term goal of this mission is to deploy a satellite cluster in lunar orbit by 2030.

2.12. **Tiantuo-3**

The Tiantuo-3 mission is composed of a 20kg main satellite, a 1kg mobile phone satellite and four 100g femtosatellites. It is developed by the National University of Defense Technology, and aims to perform on-orbit verification of technologies such as space self-organizing networks and multi-
satellite coordinated measurement and control. Tiantuo-3 was successfully launched into orbit in September 2015.

2.13. SULFRO
Space Ultra Low Frequency Radio Observatory (SULFRO), planned by the Chinese Academy of Sciences, plans to send a satellite cluster consisting of one microsatellite and 12 2U CubeSat to the Sun-Earth L2 Point to observe ultra-low frequency space radio, while exploring the evolutionary history of the universe. The satellites are equipped with micro propulsion systems to control the inter-satellites distance. In order to ensure the inter-satellites communication, the inter-satellites distance shouldn’t exceed 30km [11].

3. Development of Satellite Cluster Guidance, Navigation and Control Technology
According to the cluster missions in the previous section, investigating their GNC composition, and summarizing their inter-satellite relative navigation and orbit control methods.

3.1. GNC Configuration of Satellite Cluster
Magnetic control is a simple and effective means of satellite attitude control, because most micro-nano satellites operate in low Earth orbits. At present, the sensor of Micro-nano satellite is basically composed of sun sensor, micro-star sensor, gyroscope, magnetometer. The actuator is composed of reaction wheel, magnetorquers, micro thruster to realize the three-axis attitude control of the satellite.

Compared with ordinary small satellites, micro-nano satellites require sensors and actuators to be as light in mass and low in power consumption as possible. Therefore, it is necessary to conduct research on micro-sensors and actuators to achieve high-precision attitude control with limited space and power consumption. The current attitude control accuracy of micro-nano satellite is about 1°.

3.2. The Relative Navigation Methods
The relative state measurement is one of the key technologies to realize cluster cooperative. Due to the mature development and convenient application of GPS system, the relative navigation is mostly realized based on differential GPS. Using Satellite-borne GPS receiver to synchronously track GPS navigation satellites, collecting data and performing differential processing to realize inter-satellite tracking and measurement. The technology of relative navigation based on vision is gradually applied. It mainly uses optical sensors such as pulsed laser rangefinder and linear array scanning lidar as measuring elements to obtain the relative state directly or indirectly.
### Table 1. Typical Examples of Satellite Cluster Missions and Their Guidance, Navigation and Control Technology.

| Mission Name | Cluster members | Mission progress | Mission Information | Relative navigation | Orbit control |
|--------------|-----------------|------------------|--------------------|---------------------|---------------|
| AeroCube-4   | 3 1U CubeSats   | Launched in September 2012 | Sensor: earth and sun sensors, magnet field sensors, gyro, inertial measurement unit | Differential GPS | Differential drag |
| KickSat      | 1 3U CubeSat and 105 femtosatellites | The second mission was successful in March 2019 | Sensor: magnetometer, MEMS gyro | - | - |
| Flock        | Hundreds of 3U CubeSats | More than 300 satellites have been launched | Sensor: magnetometer, sun sensor, star tracker, gyro, horizon sensor | Differential GPS / RF communications | Differential drag/Field emission electric propulsion |
| Starlink     | 42,000 small satellites | 835 satellites have been launched | Sensor: star tracker | Optical inter-satellite link | Ion thrusters |
| Blackjack    | 60-200 small satellites | Two test satellites are expected to be launched in 2021 | Sensor: magnetometer, sun sensor, star sensor, inertial measurement unit | - | Electrospray thrusters / Cold gas propulsion |
| SWIFT        | hundreds or thousands of small femtosatellites | In the planning stage | Sensor: sun sensor, inertial measurement unit, star cameras | Differential GPS | Electrospray thrusters / Digital micro thrusters |
| Remove Debris | 1 microsatellite and 2 2U CubeSats | Complete all tasks on March 4, 2019 | Sensor: magnetometer, sun sensor, gyro | Optical inter-satellite link | Ion thrusters |
| GomX-4       | 2 6U CubeSats   | Launched in February 2018 | Sensor: magnetometer, sun sensor, star tracker, gyro | GomSpace Software Defined Radio platform | Differential drag / Cold gas thrusters |
| Tiantuo-3    | 2 micro-nano satellites and 4 femtosatellites | Launched in September 2015 | Sensor: magnetometer, sun sensor, gyro | - | - |
| SULFRO       | 1 micro satellite and 12 2U CubeSats | In the planning stage | Sensor: magnetometer, star tracker, gyro | - | Solar sailing / Micro thrusters |

#### 3.3. Orbit Control Methods of Satellite Cluster

The composition of micro-nano clusters is mostly heterogeneous, with large differences in surface to mass ratio, which can easily cause relative position drift. Due to the limitations of mass and power consumption, most micro-nano satellites are not capable of propulsion. Considering they generally operate in low-earth orbit, it is possible to use atmospheric resistance to achieve orbit control by means of differential resistance or solar sails to maintain configuration. For example, the Flock of Planet Labs used their unrolled solar panels to adjust the attitude patterns, creating different drag ratios for orbital control. In order to improve the orbital maneuvering capability, some micro-propulsion devices such as cold gas propulsion and ion propulsion are gradually being developed and applied to micro-nano satellites.
4. Conclusion
The micro-nano cluster is a strategic development direction that the world's major aerospace powers focus on. Many micro-nano cluster missions in commercial and military fields have been planned and developed abroad, and gradually entered the application stage. China is still in the preliminary experimental and research stage in the field of cluster. The research on key technologies of micro-nano cluster includes the following aspects:

1. Microminiaturization of sensors and actuators: Taking in-depth research on modules such as miniature star sensors, momentum wheels, and propulsion to improving accuracy, reducing power consumption, and reducing quality. This is the premise and basis for the on-orbit application of micro-nano cluster.

2. Inter-satellite information sharing and transfer technology: Compared with traditional formation flying, micro-nano clusters have greater communication pressure, so it is necessary to break the shackles of relative measurement and establish an overall information transfer and sharing system.

3. Distributed satellite control method: The cluster mode poses a challenge to the traditional satellite operation and control system. The centralized method is difficult to be applied to large-scale micro-nano clusters, so it is necessary to explore the global control based on local navigation information for distributed systems, while improving the self-organization ability of clusters.

4. Configuration maintenance and control technology: Not all members in the micro-nano cluster have the ability to maintain and control orbit. In addition, due to the large scale of the cluster, there may be delays in navigation information. The Leader-follower formation control algorithm and virtual structure method in the traditional formation control technology are not applicable. Considering the configuration maintenance and control technology based on bionic or artificial intelligence, while taking into account the fuel consumption and overall coordination.

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