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Concept design and cluster control of advanced space connectable intelligent microsatellite

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ABSTRACT

In this note, a new type of advanced space connectable intelligent microsatellite is presented to extend the range of potential application of microsatellite and improve the efficiency of cooperation. First, the overall concept of the micro satellite cluster is described, which is characterized by autonomously connecting with each other and being able to realize relative rotation through the external interfaces. Second, the multi-satellite autonomous assembly algorithm and control algorithm of the cluster motion are developed to make the cluster system combine into a variety of configurations in order to achieve different types of functionality. Finally, the design of the satellite cluster system is proposed, and the possible applications are discussed.

1. Introduction

The development of modern microsatellite breaks through the traditional design ideas of “A large satellite with multiple functions” [1], and advocates using the mature technology and modular, standardized hardware to simplistically design and produce satellite. The new generation of microsatellite has the advantages of light weight, small volume, low cost, short mission cycle and better performance [2]. Due to the limitation of the structure and function of single satellite, microsatellite is usually used to complete the complex space mission through the cooperation with other satellites [3]. The common configurations reported in the literature include constellation [4], formation [5], and group [6,7] which now have been applied to remote sensing [8], communication [9], navigation [10] and military reconnaissance [11], etc.

With the progress of satellite control technology and orbit assembly technologies, the satellites' cooperation pattern is becoming diversified. The Phoenix Project, which was started by the Defense Advanced Research Projects Agency (DARPA) in 2011, presents the concept of “cell satellite”. It requires the microsatellites to be physically connected to each other so as to form a large satellite system [12,13]. Tethered satellite system uses tethers to connect a number of rigid spacecrafts working in different orbits together, which has advantages of providing a larger aperture, and the capability of transforming the configuration flexibly by changing the length of tethers [14]. Furthermore, the robot cluster technology can also be used to promote the satellite cluster control technology [15]. The “Cellrobot”, developed by KEYi TECH Company from China [16], consists of many robots to form a variety of shapes, which can achieve different functions, such as combining into a mechanical arm, remote controlling cars and even humanoid robot. Radhika Nagpal, the scientist from Harvard, has successfully made 1024 Kilobot robots autonomously form the target formation through intelligent robot cluster technology [17,18].

In this engineering note, one kind of space connectable intelligent microsatellite is conceptually designed. The designed satellite group can autonomously connect to each other and realize cluster movement through drawing lessons from the connectable “Cellrobot” and “Kilobots” cluster robot. The rest of this note is organized as follows. Section 2 introduces the overall concept about the connectable intelligent satellite. Section 3 addresses the multi-satellite autonomous body assembly algorithm. Section 4 analyses the cluster motion control principle. Section 5 gives the satellite cluster system design and potential application.

2. Satellite system design

The idea of spherical satellite design is adopted, which is inspired by the “Mini AERCam” microsatellite developed by NASA [19,20]. The satellite is centimeter-sized and has external interfaces, which can autonomously connect to each other.

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2.1. Satellite system composition design

The satellite system is designed to be equipped by stereo vision camera, GPS receiver, gyroscope, solid propellant, electronic equipment, and external ports. GPS is used for position and velocity determination while gyroscope is for attitude determination. The three-axis-stabilized controller is adopted, and the Micro-Electro Mechanical System (MEMS) based solid propellant propulsion is used for both attitude and orbit control. Each satellite is loaded with a binocular stereo vision camera for target stereo imaging. The satellite is equipped with a battery, and the energy transmission mode is designed to be wireless. For the external features, the shell is embedded with interface devices. Every two satellites can rendezvous and dock autonomously through the interface devices, and achieve relative rotation through the internal motor driving. Data transmission between two satellites is also designed to be wireless, and the control of the satellite cluster is designed to use intelligent clustering algorithm.

2.2. Satellite configuration design

The satellite adopts the centimeter-sized spherical structure. The right sub-graph of Fig. 1 highlights the chips structure inside the satellite, including two GPS antennas, one GPS receiver, one gyroscope, one communication antenna, one storage battery, eight solid thrusters, four external interface devices and two binocular stereo cameras. Onboard controller computer, communication module, line boxes, image processing modules are integrated on chips, while antennas, solid propellants, binocular stereo vision cameras, external interfaces with motors are connected with the shell. Four interface devices are equidistantly embedded on the shell. One stereo camera is installed on the top while the other is mounted at the bottom of the satellite. Eight solid thrusters are evenly distributed with 45° mounting angle relative to the interface and satellite ends. Therefore, the thruster system not only can control the orbit, but also can control the attitude.

2.3. Interface device design

The interface device, depicted in Fig. 2, includes the rotating shaft, the inner ring and the outer ring. Outer ring is rigidly connected with the spherical shell, while the inner ring is connected to the out ring via ball bearings so that it can rotate along its center axis. Inner ring is also divided into internal and external parts. The former is the transmission device to achieve the function of rotation, and the latter is designed to accomplish the rendezvous and docking of two satellites. Two ends of the rotation shaft are connected with the motor and inner ring, respectively. Therefore, the interface device can rotate via torque that motor produced.

The rendezvous and docking part on the external interface takes the “bumping - telescopic rod” type, the warded lock is around the port and telescopic rod structure is at the center. The design of each interface is the same and only has one docking mode without any hermetic or communication. There are four laser measuring instruments embedded on the mating surfaces. Two satellites conduct adjustment of the relative position according to the laser measuring information during rendezvous and docking. An example of the docking operation is illustrated as follows: assuming that one interface stays still when docking starts and the other rotates around the shaft according to the laser measurement information. The rotation stops when reaching 180°, and the docking maneuver begins to approach the opposite interface until lock bumping procedure is completed. After fixing the position, a telescopic rod extends from the center of each interface and inserts into the port on the other side of the groove to complete the docking process.

3. Multi-satellite autonomous body assembly algorithm

In the auto-assembly phase, satellites among the cluster independently start autonomous docking assembly to form a predetermined configuration when the cluster satellites have reached the target areas. Fig. 3 shows the whole auto-assembly process of the cluster satellites. The auto-assembly process can be divided into two sub-phases: 2D auto-assembly and 2D-to-3D transformation. In the 2D auto-assembly phase, the individual satellites can independently change its state based on four simple rules when the cluster satellites have reached the target areas: 1) Outermost satellite move first; 2) Edge-following; 3) Two principles to decide when to stop moving; 4) Contact with the nearest accessible docking interfaces. The 2D-to-3D transformation can be easily completed by the rotational motion of the cluster satellites.

When the satellites in the cluster reach the target areas, a satellite is selected by the cluster as the seed satellite, and its gradient value is set to be zero. Then, other satellites update their gradient values and judge their locations accordingly. Next, the outermost satellite (the gradient value is the largest) move first, which moves according to the edge-following rule, and stops when it moves into the envelope of target configuration or its gradient value is equal to the closest stationary satellites. After that, all other satellites update their gradient values, and the new outermost one starts to move just as the first one. The 2D configuration is completed when all the satellites in the cluster have moved into the target shape and connected together. Finally, the cluster starts to rotate and transform the 2D configuration into 3D configuration.

The detailed running process of the auto-assembly algorithm developed in this paper is depicted in Fig. 4, and the corresponding simulation results in the Matlab environment are shown in Fig. 5. The solid blue blocks in Fig. 5 represent the final configuration to be achieved. The blue circles represent the cluster satellites that the relative position is stationary, and the red circles represent the cluster satellites that relative position is changing. It can be observed from Fig. 5 that the automatically

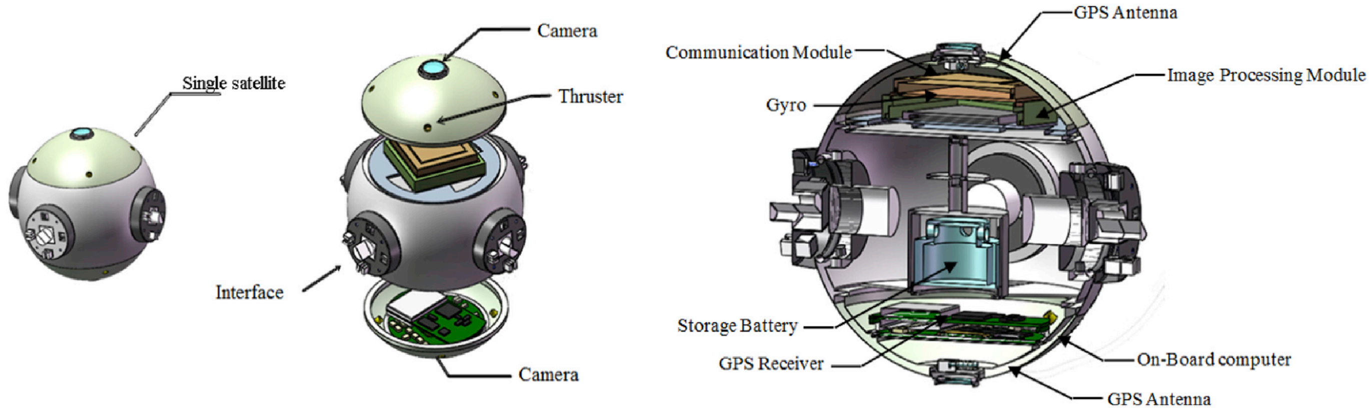

Fig. 1. Satellite system design and exploded view.