Review Article

Advances in Theoretical & Computational Physics

Relative Navigation and Control of Nano-Satellites in Formation

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Submitted: 25 June 2018; **Accepted**: 28 Aug 2018; **Published**: 24 Sep 2018

Abstract

The paper is devoted to the theoretical foundations and achievable performance analyses of control principles for a group of small satellites as a single distributed control plant. The composition of on-board navigation sensors for each small satellite in their formation is also considered. Selection of the characteristics of data transmission channels, the development of integrated systems for estimating the parameters of relative motion of satellites is made. The results of the work can be used in the design of low-orbit space-based systems for control the motion of terrestrial dynamic objects from a remote command post, including the tasks of telemedicine and mobile robotics.

Keywords: Nano-satellites, Micro-satellites, Relative navigation, Attitude and Orbital control, Relative motion control, Data exchange.

Introduction

It is widely recognized presently that the forthcoming near-Earth space systems will use satellite formations as a distributed platform for joint operation, and the role of existing conventional single satellite systems will be gradually declined. This evolution of satellites requires an essential change in the design, implementation and operation approaches for different missions [1,2]. Two tendencies are typical in the current development of unmanned space technologies and systems, in construction satellites:

- essential decrease in the mass of each satellite, making the satellites smaller with the current increase in the number of satellites launched each year;
- The increasingly common practice to design the formation of several small satellites as a distributed controlled system where the satellites jointly solve the common problems and the assigned functional tasks.

The number of the most common Cube-sat satellites launched annually exceeds 100 and is constantly growing, but most of them are extremely simple and incapable of solving the complex problems and any new meaningful tasks. The video camera and the simplest transmitter often form the basis of the "payload" of satellites for monitoring the surface from low Earth orbit. The altitude of the orbit is usually close to 600 km, which is a compromise of the requirements for a sufficiently good resolution of the images obtained and the departure of even the heavily discharged atmosphere, which prolongs the term of their operation.

For some expansion of the functionality of pico-satellites, it became possible to scale them on one side up to a double size in 2U and even up to 6U, but this did not change the fundamentally strong limitations of Cube-sat both on the dimensions of the components and on the available power onboard due to limited area of solar panels. Therefore, continuing the line of development and improvement of cheap Cube-sat, many developers began to pay more attention to the creation of controlled groups of pico-satellites in which several (at least two or three) satellites are jointly considered as a single distributed control system capable of solving more complex functional tasks, than a single satellite.

In particular, it is possible to consider the systems for stereo monitoring, control of gravity anomalies, control of the 3D-structure of ionosphere, telescopes and high-resolution radio antennas, space communication systems and data transmission with a small time delay compared to the use of high-orbit stationary satellites. To compile a 3D map of any physical parameter of near-Earth space, it is necessary to process the simultaneous measurements obtained at different satellites, knowing the mutual distance between satellites and constantly supporting it. Control of the relative positioning of satellites in such a constellation is an indispensable feature of a distributed controlled system, and besides ensuring the required formation of satellites, it is also necessary to guarantee the reliable radio or optical communication between these satellites. In fact, the last requirement is to keep the distance between satellites no more than admissible value due to the orbital control of some (or all) satellites in the formation.

Formation of Micro-Satellites

In accordance of above, the problem arises of controlling the spatial mutual position of each satellite in formation. It is also necessary to ensure the communication between two points on the Earth through the formation of low-orbit satellites.

How to keep the required mutual position of small satellites in the formation? For this purpose the onboard equipment of satellite must provide the solution of the following three tasks:

- precise relative navigation of satellites, which presuppose the required composition of on-board sensors and reliable algorithms of navigation information processing.
- precise orientation of satellites with the help of sensors of their attitude position and inertial flywheels (minimum of 3, but usually 4), creating of control moments for the correct orientation of the satellite along three axes.
- reasonably precise control of the orbital motion of each satellite or active part of the satellites in the formation, with the use of at least three effective jet engines, creating the required control force vector passing through the centre of gravity of the satellite.

Let us draw attention to the fact that the ordinary liquid jet engines are not suitable, because they require large fuel reserves. The efficient electrostatic engines with a sufficiently high thrust are needed. The modern technologies do not allow so far to place such engines at Cube-sat, especially together with flywheels, and the necessary set of linear and angular motion sensors. This makes it necessary to refuse the comprehensive use of the concept of pico-satellites and to consider satellites of large size and mass, referring them to the category of micro satellites with a mass of 10 to 100 kg.

The selection of electrostatic micro-engines for orbital control (slight correction of the orbit) of micro satellites is the most difficult task in designing the satellite formation control system and it can cause a delay in the design in anticipation of progress in the technologies for creating such electrostatic engines. In several countries, great advances have been made in the creation of powerful electrostatic engines for interplanetary spacecraft, but they are not applicable to micro satellites. To correct the orbit in 3D space, on each satellite, it is necessary to install three small-sized engines that create sufficient thrust, but with very small power consumption, taking into account its shortage on board a micro satellite. The authors have not yet been able to find an acceptable solution of this problem. If progress is not achieved in the near future, it will be necessary to increase the mass and size of the satellites, but this in turn will require greater efforts from the engines and from the controlled flywheels for angular stabilization of the satellite. By the way, in fact, it should not be pure stabilization, but rather precise control of the angular position in the process of pointing the on-board antenna to the desired point on the surface of the Earth.

It is important to analyze the possibilities of constructing a controlled formation of micro satellites and estimate the appropriate composition of the on-board equipment of such satellites.

Certainly that when solving the problem of relative navigation of low orbiting satellites, the most efficient on-board sensor could be a special GPS / GLONASS receiver that realizes a differential mode of operation, because it is required to measure not the absolute position of each satellite, but their difference in the differential mode [3]. When using phase processing, the error in differential measurements can be measured in several millimeters, which in principle exceeds the capabilities of any other position sensors, including laser ones. However, in practice, when implementing such an approach, the developer has at least three serious difficulties:

1. Any SNS is designed for efficient operation at ground and possibly at airplane altitudes, but not at an altitude of 600 km. Most receivers have restrictions on the altitude and speed of the carrier, including, among other things, the concern of SNS military owners to prevent "unauthorized" use of receivers available on the free market. Particular care requires ensuring the radiation resistance of receivers and especially the processor.
2. The high velocity of the controlled low-orbit satellites in relation to the navigation satellites leads to a very rapid change in the constellation of the operating navigation satellites, and the need to upgrade the embedded program code of GPS navigation receivers and especially GLONASS receivers. In this condition a serial cheap receiver cannot be used.
3. Attempts by developers of hand-crafted satellites to reprogram the embedded code of satellite receivers usually preclude obtaining a license to launch a satellite from the national Space Agency, designed to guarantee the safety (in a broad sense) of launching and operating a satellite. This practically closes the possibility of free space application of SNS receivers, especially GLONASS. Perhaps, with the advent of new global satellite navigation systems, the situation will become less tense.

The Necessary Equipment of Satellites in Formation

In case of extreme need to measure the relative position of satellites in the formation, it is possible to build a special short-range radio navigation system, all components of which can be placed on satellites, which will further exacerbate the problem of the available volume and energy consumption at the satellite. It does not make sense to build a special global navigation system for servicing the formation of low-orbit satellites, but someday it will be possible to create a SNS suitable for navigating both ground, airplane and space vehicles with the more favourable regime for the latter.

Using a laser meter for distance between the satellites in principle can also provide millimetric accuracy, but it requires a very difficultly realizable direction of the laser beam exactly on a controlled satellite with an angular error of no more than 10^{-1} angular minutes, taking into account the errors in calculating the direction to the neighboring satellite, and the errors of angular stabilization. It is important, however, that the measurement of not only the distance but also the direction of the line connecting the satellites is required to control the formation of satellites. The hope for the successful operation of such a laser meter is small.

Taking into account the above, let us consider the opto-electronic system of relative navigation of satellites as the main one. In favour of this choice, there is a rapid increase in all the most important consumer characteristics of video cameras and their permanent cheapening [4-7]. When choosing the spectral range of video cameras, it is necessary to take into account the danger of their exposure by intense sunlight and the actuality of work in the dark by the infrared image.

It is reasonable to divide the possible satellite opto-electronic navigation systems into two groups: using markers based on LEDs at satellites, and using contour image processing without special markers. The first option is more reliable and accurate in evaluation of the parameters of relative navigation in any conditions, except the case of too big distance between satellites. However, it requires placing on each side of the satellite hull (practically at all controlled satellites in the formation) several scattered LEDs, preferably with different colors of light. This equipment, as well as video cameras with a wide spectral and angular range, should be presented at all satellites in the formation. The size of the resulting images in pixels with known dimensions and shape of each satellite may be easily recalculated into the parameters of the relative navigation of satellites in meters and degrees. The accuracy of such estimation of navigational parameters depends on the resolution of the video camera and on the distance between the satellites [6-8]. The permissible resolution of a video camera depends not only on its perfection and cost, but also on the available power of the processor for processing video images. With a distance between satellites of about 100 m and a good resolution of a modern video camera (more than 640 x 480 pixels), the error in measuring the distance between satellites can be no more than 10 cm [7].

Different optoelectronic systems have been long widely used in space and have proven themselves well. They are successfully used in the tasks of orientation and control of the ISS, spacecraft and satellites with the analysis of video images of the space object and the starry sky, the problems of directing the optical equipment to specified areas of the earth's surface, and correlation-extreme navigation. However, there are not many published materials on the relative navigation of micro satellites yet. Several articles describe the results of simulation the approach of two satellites, one of which (the main one, the active one) is equipped with an optical camera, and the other (passive) is represented only by its known dimensions, and sometimes (for example, when collecting space debris) does not even have known sizes and shapes. Variants of the formulation of the problem of relative navigation can be numerous, both in the distribution of the role of individual satellites in this process, and in the composition of the actuators used in angular and orbital control.

Sometimes, when choosing the composition of sensors for relative navigation, it is also justified to use inertial means, which, in combination with position sensors, make it possible to construct an invariant measuring system without a dynamic error. However, this problem in the considered set of problems is less relevant in connection with sufficiently fuzzy maneuvers of the object with low-power actuators. As a result of the improvement of MEMS technologies, further increase in the accuracy of miniature gyroscopes and accelerometers is expected, and then the advisability of using them on controlled micro-satellites will become more evident. While the accuracy of MEMS is not large enough to significantly improve the accuracy of the relative navigation of satellites, the expediency of using them is not obvious.

The problem of measuring the distance between the micro-satellites was considered by the authors in [4-7].

Possible Data Exchange Channels Between Low-Orbit Micro Satellites

The data exchange through the communication channels is absolutely necessary for the implementation of any micro-satellite mission. The structure of the network of such channels depends on many circumstances and has to be optimized for each specific project. In the general case, it is possible to consider the features of constructing the three types of channels in the overall structure.

a) A channel for exchanging information and data between two micro-satellites.
If the small distance between satellites is kept, this channel can be built on the basis of short-range radio systems without directional antennas (Short Range RC) such as ZigBee, Bluetooth or Wi-Fi. All three systems guarantee a communication range of at least 100 m, but the data transfer rate is low and this can create essential problems in the implementation of the formation. The task of remote control of robots through low-earth orbit satellites may require speeds of up to 100Mb/s, and only a Wi-Fi and probably ZigBee system can approach this performance. This will require a fairly powerful power supply, which is also a problem on board. Nevertheless, the option of non-directional radio communication between closely flying micro-satellites seems to be the most promising.

b) A channel for data transmitting from a microsatellite to the desired point on the ground.
This channel is the most difficult to implement in practice with limited micro-satellite sizes and the requirement to provide a significant data transfer rate (up to 100Mb/s) with high noise immunity of the channel. In this case, it is necessary to focus not just on radio emission directed toward the receiver located on the ground, but on a narrow (about 10^0 wide) radiation pattern of such antenna. The antenna should be narrowly focused. From the experience of previous developments, it is possible to estimate the power of radio transmitter in 100w necessary for reliable data transmission, which can be assembled from solar batteries with an area of approximately $0.1m^2$. Assuming the power of all other electric power consumers aboard (including electrostatic jet engines and flywheels) is also not more than 100w and taking into account the saturation of the satellite for about half of the flight time and other losses, it is possible to estimate roughly the required area of illuminated solar cells in $0.4\ m^2$, which will give a linear size of the design of the satellite in 0.6-0.7 m. Note that in order to construct antennas with a diagram width of 10^0 its linear dimensions (for the Ku- or X-band frequencies) should be about 1.5m, but when the satellite is launched, the antenna can be folded to a size of 0.6m and deployed already in space. The above circumstances force us to abandon the concept of Cube-sat (even U6) and consider the concept of a controlled micro-satellite with a side of 0.6-0.7 m, a mass of about 20 kg and one narrow antenna, as promising for our projects. The formation should be at least with two such micro-satellites.

c) A channel for data transmitting from moving ground vehicle to the micro-satellite.
This channel is realized easier than channels a and b, since the radio transmitter power available on the ground can for a short time considerably exceed 100w even on mobile robots, and even more it at the stationary objects. The receiving antenna on the satellite can coincide with the transmitting antenna on the satellite, oriented to the desired point on the ground. The speed of data transfer from earth to satellite (and then through the second satellite to another point on the ground) can be about 100Mb/s using the most advanced technical solutions, including efficient algorithms of information compression.

Application of Low-Orbit Micro-Satellites in the Projects E-Sit and TMA

The analyzed concept of a controlled formation of micro satellites is mainly developing in the interests of the international project E-SIT (European Centre for Space Informatics and Telecontrol) proposed by the authors for remote control of robots from a command post through the formation of low-orbit micro-satellites. A part of E-SIT project is the extremely relevant now in Russian TMD project (telemedicine of actions) to ensure a high quality of diagnosing the health status and timely medical assistance for the population of Russia based on the information technology of telepresence and telecontrol.

The project assumes remote control of *n* robots from a remote command post, n≥1. Each robot has its own navigation system, which allows measuring the current position. The command post (CP) is located at a great distance from the robot, but its coordinates are known. The CP must send control commands to the robot and receive from it information and data used for control. The task is to create a communication channel "CP-robot". The block-diagram of E-SIT system in TMA is shown in Figure 1.

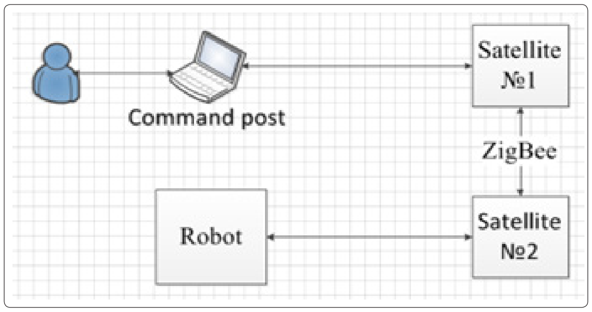

Figure 1: The block-diagram of E-SIT system in TMA at n=1

The use of the Internet for data transmission is excluded for several reasons, one of which is a significant time delay in the transmission of signals through communication satellites at the geostationary orbit. A forward and reverse signal transmitted through high-orbiting satellites have a delay of about 0.3s, which worsen the quality of control system [9,10].

Therefore, it is necessary to build a «CP-Robot» space communication system based on low-orbit satellites with an orbit altitude of about 600 km. Then the signal delay is reduced by two orders of magnitude compared with the stationary satellite that is almost to zero. Also, the reliability of the space communication system will be improved without using Internet, especially if there is structural redundancy on low-Earth orbit satellites.

Each of (n+1) small satellites has one narrowband antenna pointing to the robot or CP location. The relative motion control system allows a small removal of satellites from each other, which does not exceed a specified value of the order of 30-100 m. Such a formation of micro satellites allows them to exchange continuously information by non-directional radio links with low power consumption, and eventually realize the concept of remote control of robots based on the formation of rather cheap low-orbit micro-satellites [11,12].

Conclusion

The concept of a controlled formation constructing of micro-satellites for remote control of robots is proposed and analyzed. The requirements for the on-board equipment of satellites, to their mass and dimensions, to the rate of data transmission through communication channels, to the accuracy of controlling the relative motion of satellites are estimated. The made estimations can be corrected in process of the profound analysis of all circumstances of construction of the offered space system.

Acknowledgments

The work was supported by the Ministry of Education and Science of the Russian Federation, assignment 9.1559.2017 for 2017-2019.

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