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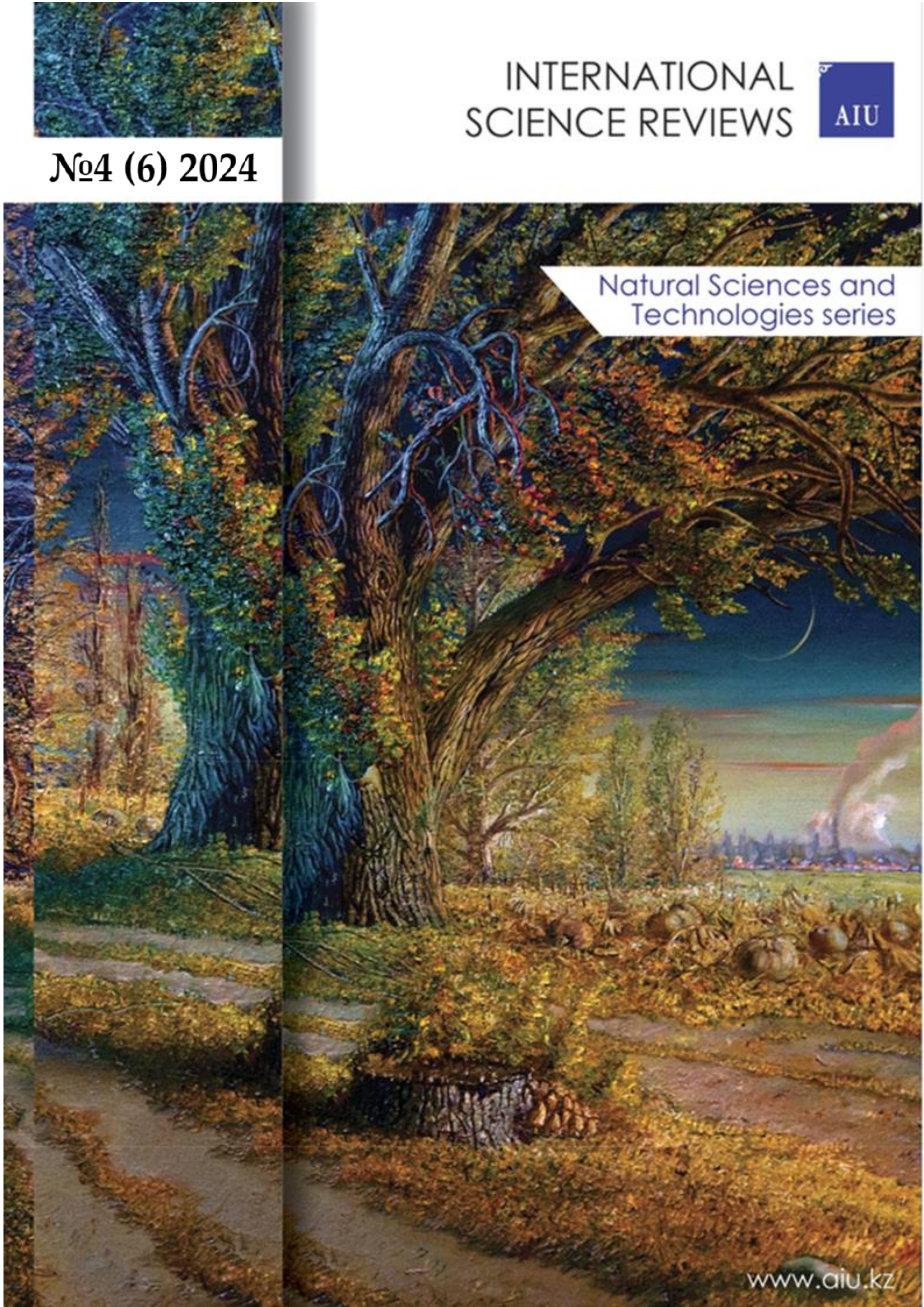

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CONTENT

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Analysis of the requirements for satellite constellation control

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Abstract. Currently, Kazakhstan has started to develop, design and build micro- and nanosatellites that can be used for remote sensing, communications and the Internet of Things. These tasks involve the use of a constellation of up to 20 or more satellites. In this regard, the task of constellation control arises to fulfill the set goals. In this article we review open sources on the issues of satellite constellation control to identify the main tasks and problems arising in the fulfillment of flight missions. It is shown that constellation control is reduced not only to the preservation of the geometry of their location, which is set to perform a particular task, but is associated with the prevention of collisions between satellites during various maneuvers, due to space debris or other satellite. During maneuvers it is also necessary to minimize propellant consumption, i.e. optimize the routes of the satellites relative to each other. All these problems require their solution when creating a software product for satellite constellation control. Based on the analysis of literature sources, the requirements for satellite constellation control are formulated taking into account reliability, system flexibility, optimization of propellant consumption and compliance with international rules and guidelines for space operations.

Keywords. Satellite, motion control, flight task, space debris, satellite constellation.

Introduction

Over the past decades, aerospace technologies have had an increasing impact on the economic and social development of the state and society, finding wide application in various fields of the national economy and the defense industry of the republic. In accordance with the Strategic Development Plans[1-3] implemented in the country, competitive space technologies, products and services are currently being actively introduced in the republic in the interests of Kazakhstan. High-tech, dynamically developing enterprises of the space industry have been created, which are capable of independently designing, creating and operating competitive space systems, as well as providing high-quality services in demand on regional and global markets.

Currently, the capabilities of small satellites and miniature payloads have greatly increased, as well as new business models based on large-scale low-orbit constellations consisting of inexpensive, mass-produced satellites. Small satellites usually require lower development and launch costs, which makes them more affordable for most organizations and countries. This accessibility attracted the attention of both commercial companies and academic institutions, as it allowed them to contribute to space research.

The potential of CubeSats or nanosatellites is widely used to accelerate scientific and technological progress in emerging and developing countries. Analytical studies and forecasting show that at least 2,000 nanoclass satellite will be launched into space during the period from 2023 to 2027 [4,5].

The commercial availability of nanosatellite elements (Earth remote sensing (ERS) imagers and communication tools for control and downlink of information from low-orbit CubeSats in the S and VHF bands) and the absence of restrictions on their acquisition make it possible to develop this area in Kazakhstan as an independent space industry. The large territory of Kazakhstan with a diverse relief, including mountainous terrain, which occupies 10%, as well as deserts and semi–deserts - 25% of the total area, where a significant part of the population lives and the state border passes, requires constant monitoring and continuous communication (including special one), in accordance with the solution of strategic development tasks of the Republic of Kazakhstan [3]. The Aerospace Committee of the Ministry of Digital Development, Innovation and Aerospace Industry of the Republic of Kazakhstan and Ghalam LLP signed an agreement to carry out work on the creation of a constellation of medium-resolution remote sensing satellites KazEOSat-MR. The project is aimed at replacing the current medium-resolution remote sensing satellite "KazEOSat-2" and developing products and services provided on the basis of reliable and operational remote sensing data. This will meet the needs of government agencies and organizations, as well as small and medium businesses in geospatial data built on their basis [6].

Creation of remote sensing satellite constellations involves real-time flight control, in accordance with the tasks set. Satellite constellation control is a complex multiparametric mathematical problem that takes into account changes in satellite orbits under the influence of external disturbing factors, propellant reserves for orbit correction, maneuvers for flight missions, etc. To date, software products for managing satellite constellations have not been developed, although work has been carried out on orbital calculations [7].

Overview of works on satellites constellation control

A remote sensing satellites formation flight is defined as a coordinated flight of multiple satellites in low Earth orbits to perform common tasks. These satellite constellations are designed to provide continuous and stable coverage of certain areas or the entire Earth's surface. These systems require high accuracy in maintaining orbital parameters, reliable communication, and the ability to quickly reorganize in the event of failure of individual vehicles.

Several schemes of group flight of satellites and their evolution over time are considered in the work [8]. The flight patterns of satellite constellations are based on the equations of relative motion in two-body dynamics, better known as the Hill equations [9]. When disturbances disrupt satellite constellations, maneuvers are calculated to maintain the constellation. The suitable concept of formation flight of synthetic aperture radar (SAR) satellites is discussed in [10]. This scheme is capable of implementing complex basic conditions for SAR interferometry, while minimizing the risk of collision associated with rendezvous operations. The orbit controlmethod is presented and the corresponding strategyis confirmed, as well as an effective implementation of the distributed satellite concept is proposed.

The authors of [11] presented algorithms for cluster flight of satellites in low Earth orbits. To limit the relative movement distance, requirements for the initial conditions of the modules have been developed. The accompanying analytical estimation of the relative distance between the modules is proved on the basis of a design model assuming the immutability of environmental disturbances over time. In addition, this article presents a detailed pulse algorithm for creating and maintaining a cluster to track a given nominal orbit, the characteristics of which satisfy the previously developed no-drift constraint. This algorithm ensures propellant balancing between maneuvering modules, as well as minimizing total propellant consumption, while ensuring collision-free movement.

The results of a study of the possibility of formation flight of nanosatellites in the QB50 project are presented [12]. This is a mission to create an international network of 50 nanosatellites for multipoint measurements in situ in the lower thermosphere and atmospheric re-entry studies. The possibilities and problems of formation flight of satellites are systematically identified and analyzed. The work [13] is also devoted to the analysis of the constellations of small satellites. In particular, various missions using CubeSats are considered, where formation flight schemes will be applied. These missions are classified according to the missiontype, mission status, number of satellites, lead organization, source of funding, and flight requirements of the constellation.

The issue of designing the trajectory of the constellation's satellites for collecting solar energy in space and transmitting it to Earth using a microwave beam is considered in [14]. To perform the appropriate orbital maneuvers, an optimization system is being developed using the Hill-Clohessy-Wiltshire equations [15,16] to achieve the dual purpose of maximizing the transmitted power and minimizing the amount of propellant needed to perform the desired orbital maneuvers. It is shown that the use of periodic relative orbits reduces propellant consumption 3 times.

One of the critical issues of satellite constellation control is the calculation and implementation of corrective maneuvers. Quite a lot of work is devoted to this issue [17]. Here we are talking about maneuvers to avoid collisions with space debris. In this article, a method has been developed for choosing the timing of evasion maneuvers with minimal propellant consumption without violating the limits of the maximum inter-satellite distance between clusters. To assess the maneuverability, the average difference in the large semi-axis between the maneuvering satellite and other satellites is monitored. Three methods of searching for optimal maneuvers in conditions of cluster content are proposed. The first is to perform an additional maneuver to hold the cluster during maximum approach to debris, the second is a global maneuver for all clusters, and the third is a maneuver with optimal propellant consumption, which includes restrictions on cluster retention in the calculation of the evasion maneuver. The first method turns out to be the most economical. The global maneuver guarantees limited inter-satellite distances, as well as a balance of propellant and mass. The latter method proves useful at certain points in time and represents a compromise between propellant consumption and the number of maneuvers.

The review [18] examines developments in the control architecture of various satellite constellations, as well as ways to control the movement and orientation of satellite constellations. In [19], various flight control scenarios of the satelliteconstellation are discussed. These scenarios can be divided into two categories: the leadersatellite with advanced sensors and the follower satellite with common sensors. In order for all the leader satellite to maintain the desired relative configuration and simultaneously fly at a constant speed, an algorithm for jointly controlling the formation of the constellation geometry isproposed for each leader satellite. To control the follower satellite, a distributed trajectory retention control algorithm is proposed. One of the main advantages of the proposed algorithms is the ability to avoid collisions among all satellite by equipping it with an omnidirectional short-range relative distance sensor and using the methodology of potential functions. The work [20] provides a detailed overview of various missions, the mathematical foundations of control, guidance requirements, an overview of the on-board control systems used, and relative control technologies.

The issue of planning the survey of areal objects by constellation satellite is considered in [21]. The authors cited the main limitations and criteria for evaluating the effectiveness of the work schedule of the satelliteconstellation and proposed a methodology for drawing up a work plan for the target equipment of the remote sensing satelliteconstellation for the effective use of resources to optimize the process of shooting an area observation object.

The problem of limited flight control and collision avoidance for satellite clusters using inter-satellite flight boundaries is considered in [22]. The authors of this work proposed a new method for managing a cluster of satellites using a set of artificial potential functions. The proposed cluster control method is based on the boundaries of inter-satellite flight so that satellites can autonomously converge to a given boundary range, rather than on a set of precise orbit configurations. The analysis of the model shows that the method has great potential in managing clusters of microsatellites. On the other hand, this article also focuses on collision avoidance as a key requirement for a satellite cluster. The satellites of the constellation can adjust their real-time control efforts according to data on nearby satellites, reflecting the characteristics of swarm intelligence.

An interesting approach to the reconfiguration of a satellite constellation based on convex optimization and a genetic algorithm is considered in [23]. This article presents a new approach to the autonomous reconfiguration of distributed space systems, which ensures the safe guidance of satelliteconstellations according to specified schemes while optimizing total propellant consumption. The orbital transition is reduced to the form of a convex optimization problem to ensure fast calculation of control laws. Two methods are proposed, depending on the organizational architecture of the formation of the satellite. In the first, the maneuver is fully planned by the reference satellite, which defines the final tasks and control actions for the entire cluster. As a second method, a distributed version of the algorithm is proposed: tasks are sorted by reference satellite, and transition orbits are calculated by using the computing resources of the entire cluster. Both methods ensure a safe transition of the constellation to the target geometry. The simulation results show that when relative distances are on the order of hundreds of meters, the reconfiguration of LEO clusters during one orbital period requires an average value of Δv per satellite of the order of 0.1 m/s.

Interestingly, the question of autonomous reconfiguration of the flight of a constellation of SAR satellites with continuous monitoring in operation has been raised [24]. Satellite constellations can use different observation modes associated with different relative orbit configurations, as well as switch between these modes in accordance with flight control requirements. This article discusses a hypothetical constellation of SAR satellites providing interferometry, tomography, or mirror detection. The main task for this constellation is formulated, which consists in performing a reference maneuver relative to the orbit of the main satellite. This problem is solved using a feedback control law based on the newly introduced relative orbits elements and suitable for continuous-action engines with limited thrust. The asymptotic stability of the maneuverable orbit tracking problem for near-Earth, non-equatorial and near-circular main orbits is proved. It is also proposed to distribute the control along the orbit to reduce propellant consumption and transition time between SAR modes. The theoretical results are confirmed by modeling controlled transitions between different data collection modes.

The authors of [25] have compiled a fairly detailed review of the work on the use of artificial intelligence (AI), including machine learning, in solving satellite communication problems, in particular, in resource management, network control, network security, spectrum management and energy use in satellite networks. This work is a general overview of AI, including the basic concepts of AI, machine learning, the use of AI in satellite communications, obtaining telemetry, accounting for signal reflection in the ionosphere, satellite energy control, etc.

Perhaps one of the most detailed reviews of recent years on satellite constellation modeling and control is the work [26]. Three types of constellation architectures are considered: «Multiple input – multiple output» (MIMO), in which the constellation is considered as a single object with several inputs and several outputs; «Leader-Follower»(LF)constellation, in which individual satellites are hierarchically connected; and virtual structure is as the formation of a virtual structure (VS) or cyclic architecture, in which satelliteare considered as solids embedded in a common virtual solid. The «Multiple input - multiple output» architecture differs from others in its optimality and stability. However, the use of all states of the system leads to the need to place high demands on the exchange of information, so such algorithms are usually unstable to local failures. The Leader-Follower architecture uses information only about the leaders, which makes it easier to navigate through the constellation. The cyclic architecture is an intermediate link between the LF and MIMO architectures.

The method is proposed for the operational assessment of the effectiveness of the constellation of remote sensing satellites in [27]. In this article, the architecture of a real-time estimation model for remote sensing satellite clusters is proposed. First, a simulation model of the interaction of the metaphysical fields of a satellite cluster is being created to monitor moving targets. In addition to considering the effects of on-board resource limitations, it also examines the effects of image uncertainty on observational results. Secondly, a system of indicators for observing moving targets is being developed, reflecting the actual effectiveness of a cluster of satellites in orbit. At the same time, in order to increase the independence of the indicator system, a method of screening indicators using correlation analysis is proposed. Third, the neural network is designed and trained for stakeholders to provide a quick assessment. Various network structures and parameters are comprehensively studied to determine an optimized neural network model. Finally, based on the experiments conducted, the proposed neural network evaluation model can generate high-quality evaluation results in real time. Thus, the validity of our proposed approach is justified.

The analysis of reliability, fault tolerance and energy efficiency of satellite cluster control is discussed in the book [28]. The issues of on-board data processing in satellite communications using artificial intelligence accelerators are considered in [29].

Finally, we can point out another new review on modeling the dynamics of a formation flight of satellites [30]. This study is aimed at developing a model for representing the relative dynamics of satellites in circular and elliptical orbits and establishing the relative motion of satellites based on orbital elements. In the study, the authors consider the distance between the leader and follower satellites to be insignificant. A linear, time-varying approach was adopted for the study. The equation of motion of satellites in circular and elliptical orbits is derived and solved. Numerical simulations were carried out to determine the relative trajectory of the satellite in all three planes and the reliability of the developed model was thoroughly tested.

Conclusion

Creating and control of a remote sensing satellites constellation is a rather difficult engineering and mathematical task. Orbit control in the context of a formation flight of satellitesrequires precise coordination and continuous correction. Effective orbit control is necessary to ensure stable operation of the constellation, mission fulfillment and avoidance of satellite collisions.

The analysis of literary sources allows us to formulate the following requirements for satellite constellation control, which will be used when creating a software product for controlling satellite constellations.

• The satellite system must be designed in such a way as to minimize the risks of failure and guarantee a high level of reliability of operation. The distribution of satellites in the constellation should be optimal to ensure constant communication between the satellites and the ground control complex. The energy consumption of satellites should be optimized to increase their lifetime. In addition, a high level of protection of the transmitted data and high speed of data processing and transmission must be ensured.

• Planning the trajectories of individual satellites in a constellation to ensure a predetermined position relative to each other in order to achieve the overall objectives of the mission. Trajectory planning includes consideration of orbital mechanics, propellant consumption, and avoiding collisions with other satellites or space debris.

• Effective communication and coordination between satellites within the constellation is necessary to perform maneuvers, exchange data and maintain synchronization. This may include inter-satellite communication channels, ground control centers, or autonomous decision-making algorithms implemented on board satellites.

• The creation of redundancy and fault tolerance in formation is essential to ensure mission continuity in the event of satellite failures. Redundant systems, cross-support capabilities, and distributed control architectures can enhance the sustainability of the formation.

• Formation flight systems should be designed with flexibility in mind to adapt to changing mission requirements or operating conditions. This may include the ability to reconfigure formations, adjust trajectories, or deploy additional satellites as needed.

• Ensuring time synchronization. Achieving accurate time synchronization between satellites within a constellation is necessary for coordinated operations such as data aggregation, interferometry, or distributed sensing. Accurate time storage systems and synchronization protocols are used to ensure time synchronization.

• Compliance with international rules and guidelines for space operations, including space debris mitigation measures, frequency coordination and orbital zone allocation, is essential to ensure the safety, sustainability and legality of formation flights.

These requirements will be used to develop a technical specification for a software product for managing satellite constellations in Kazakhstan.

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Ғарыш аппараттары топтамасын басқаруға қойылатын талаптарды талдау

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Аннотация. Қазіргі уақытта Қазақстанда Жерді қашықтықтан зондтау, байланыс және Заттар интернеті үшін пайдалануға болатын микро - және наноспутниктерді әзірлеуге, жобалауға және құрастыруға кірісті. Бұл міндеттер 20ға дейін немесе одан да көп спутниктерден тұратын топтамаларды қолдануды қажет етеді. Осыған байланысты қойылған мақсаттарды орындау үшін топтамаларды басқару міндеті туындайды. Бұл мақалада ұшу тапсырмаларын орындау кезінде туындайтын негізгі міндеттер мен проблемаларды анықтау үшін спутниктік топтамаларды басқару мәселелері бойынша ашық көздерден алынған мәліметтерге шолу жасалады. Топтаманы басқару белгілі бір тапсырманы орындау үшін берілген аппараттардың орналасу геометриясын сақтауды ғана емес, сонымен қатар ғарыштық қоқыстарға немесе басқа ғарыш аппараттарына байланысты әртүрлі маневрлер кезінде спутниктердің бір-бірімен соқтығысуын болдырмауды да қамтитыны көрсетілген. Маневрлерді жүргізу кезінде жанармай шығынын азайту, яғни.спутниктердің бір-біріне қатысты қозғалыс маршруттарын оңтайландыру қажет. Ғарыш аппараттар топтамасын басқаруға арналған бағдарламалық жасақтаманы жасау кезінде бұл міндеттердің барлығын шешу қажет. Әдеби дереккөздерді талдау негізінде жүйенің сенімділігін, икемділігін, жанармай шығынын оңтайландыруды және ғарыштық операцияларға қатысты халықаралық ережелер мен нұсқаулықтарды сақтауды ескеретін спутниктік топтамаларды басқаруға қойылатын талаптар тұжырымдалған.

Түйін сөздер. Ғарыш аппараты, қозғалысты басқару, ұшу тапсырмасы, ғарыш қоқысы, спутниктер топтамасы.

Анализ требований к управлению группировкой космических аппаратов

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Аннотация. В настоящее время в Казахстане приступили к разработке, конструированию и постройке микро- и наноспутников которые могут использоваться для дистанционного зондирования Земли, связи и интернет вещей. Эти задачи предполагают использование группировки достигающих 20 и более спутников. В связи с этим возникает задача управления группировкой для выполнения поставленных целей. В данной статье проводиться обзор из открытых источников по вопросам управления группировками спутников для выявления основных задач и проблем, возникающих при выполнении полетных заданий. Показано, что управления группировкой сводиться не только к сохранению геометрии их расположения, которая задается для выполнения определенного задания, но связана с предотвращением столкновений спутников между собой при различных маневрах, из-за космического мусора или других космических аппаратов. При проведении маневров также необходимо минимизировать расход топлива, т.е. оптимизировать маршруты движения спутников относительно друг друга. Все эти задачи требуют своего решения при создании программного продукта для управления группировкой космических аппаратов. На основании анализа литературных источников сформулированы требования к управлению спутниковыми группировками учитывающие надежность, гибкость системы, оптимизацию расхода топлива и соблюдение международных правил и руководящих принципов космических операций.

Ключевые слова. Космический аппарат, управление движением, полетное задание, космический мусор, группировка спутников.