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DEVELOPMENT OF MOTION CONTROL ALGORITHMS OF SATELLITES IN THE FORMATION

ANNOTATION

Dissertation for the degree
Doctor of Philosophy (PhD) in specialty
“6D074600 – Space Engineering and Technologies”

General Description of the Work. The dissertation is devoted to the study of the problem of maintaining the tetrahedral configuration of a formation of satellites, which are the optical elements of a telescope with a synthetic aperture for continuous monitoring of the Earth's surface. The dissertation work examines algorithms for controlling the configuration of a formation of satellites taking into account various disturbing forces.

Relevance of the Work. Currently, in the tasks of space exploration, an increasing number of researchers prefer to consider spacecraft formation instead of single satellites. This is due to the fact that formation, use small devices, the development of which takes less time and money. In addition, with the help of satellite formations, it is possible to solve a whole class of new problems that cannot be solved by one satellite. For example, simultaneous measurement of any indicators at different spatial points, which is important when studying magnetic or gravitational fields, the ionosphere, atmosphere, etc. It is also interesting capabilities of satellite formations for the tasks of astronomical observations, stereographic imaging of the Earth's surface, and remote sensing of the Earth in real time. Along with new opportunities for researchers, new challenges also arise. One of the key tasks when carrying out a mission by a sayellite formation is to build a control system to maintain or rearrange the satellite configuration. Depending on the mission, various configurations are selected, and in each case the control algorithm is developed for the assigned tasks.

Therefore, the development of algorithms for controlling interferometers formed by a formation of satellites, taking into account various disturbing factors such as the inhomogeneity of the Earth’s gravitational field, disturbances arising from the attraction of third celestial bodies, or disturbances arising from solar radiation pressure is an urgent scientific and technical problem of great applied importance.

The developed control algorithms described in this thesis ensure that the tetrahedral configuration of the satellite formation is maintained with high accuracy.

The aim of this work. Construction of a mathematical model of the movement of a formation of satellites of a small cluster in geostationary orbit, taking into account disturbances, as well as the development of algorithms for controlling the motion of the formation to maintain its configuration.

The tasks of the work.

– construction of a mathematical model of the formation motion taking into account disturbances arising from the nonsphericity of the Earth, as well as lunar-solar disturbances;

– development of algorithms for controlling the formation motion in geostationary orbit based on linear and nonlinear methods:

1) based on the root method (RLM) and linear quadratic regulator (LQR);
2) based on the method of placing poles in LMI areas, LQR and linear H_2 control;
3) based on robust control algorithms such as H_2 and H_∞.

The research methods. Fundamental laws of theoretical and celestial mechanics; proven analytical and numerical methods of the theory of linear differential and algebraic matrix equations; application of well-known proven methods of control theory, theory of oscillations and motion stability, theory of higher algebra; high-precision numerical methods designed for solving linear and nonlinear differential equations.

The scientific novelty of the problem For remote sensing of the Earth in real time, it is proposed to use a formation of satellites of a certain configuration in geostationary orbit. The configuration is a four-satellite system, with a leader satellite and three follower satellites forming a tetrahedron. In this case, the main satellite moves in an orbit called the reference orbit. Over time, the reference orbit evolves under the influence of external disturbances, these same disturbances affect the relative position of the satellites in the formation, which entails instability of the configuration and the impossibility of completing the assigned mission.

In this regard, the scientific novelty of the problem lies in the need to develop a control system for a formation of tetrahedral configuration in the cases of perturbed and unperturbed reference orbits of the leading satellite, taking into account the figure of the Earth, disturbances from the gravitational fields of the Moon and the Sun and uncertainties.

The scientific positions proposed for defense include.

– mathematical model of the satellite formation motion in geostationary orbit, taking into account disturbances of high orbits;

– algorithms for controlling the formation configuration in the case of an unperturbed reference orbit based on the root method (RLM) and linear quadratic regulator (LQR).

– algorithms for controlling the configuration of a formation of satellites taking into account the main disturbing forces, in the case of an unperturbed reference orbit, based on the application of the method of placing poles in LMI areas, linear-quadratic regulator (LQR) and linear H_2 control.

– control algorithm ensuring preservation of the formation configuration in the case of a disturbed reference orbit and uncertainties of various kinds, based on robust control algorithms such as H_2 and H_∞.

The main results of the research.

– A mathematical model of the motion of a formation of satellites in the case of an unperturbed reference orbit has been developed. A study of the uncontrolled movement of satellites in a formation was carried out. As a result of the study, the need

to use certain control algorithms to maintain the formation configuration was shown. Algorithms for controlling the formation configuration in the case of an unperturbed reference orbit are constructed based on the root method (RLM) and linear quadratic regulator (LQR);

– A mathematical model of the motion of a formation of satellites in the case of an unperturbed reference orbit has been developed, taking into account the main disturbing forces caused by the gravitational influence of the Earth, Moon and Sun. During the study of uncontrolled motion, the need to introduce control in the early stages of flight was determined. Algorithms for controlling the configuration of a formation of satellites were constructed, taking into account the main disturbing forces, based on the application of the method of placing poles in LMI areas, linear-quadratic regulator (LQR) and linear H_2 control;

– A mathematical model of the motion of a formation of satellite relative to a perturbed reference orbit has been developed based on a modification of the Lawden-Sedwick-Schweigard model. Equations of the perturbed motion of a formation of satellites are constructed in the case of a perturbed reference orbit, taking into account perturbations due to the inhomogeneity of the Earth's gravitational field, perturbations due to the gravitational forces of the Moon and the Sun, as well as due to the solar radiation pressure. A numerical solution was carried out for linearized nonlinear equations of motion of a formation of satellites relative to a perturbed orbit. Also, a control algorithm has been developed that provides a sufficeent level of formation stability in the case of a disturbed reference orbit and uncertainties of various kinds, based on robust control algorithms such as H_2 and H_∞.

Scientific novelty of the obtained results. In this work, a solution was obtained to a mathematical model of the relative motion of a formation of satellites using proven analytical and numerical methods of the theory of differential equations, which makes it possible to study the dynamics of the interconnected movements of spacecraft in the presence of disturbances characteristic of high and geostationary orbits. A mathematical model was built relative to unperturbed orbits, corresponding to the Hill-Clohessy-Wiltsher and Lawden models. Disturbances such as the inhomogeneous gravitational field of the Earth, according to the Sedwick-Schweigard model, the gravitational pull of the Moon and the Sun, and the solar radiation pressure were taken into account. The control system and selection of control coefficients were built on the basis of such methods as linear-quadratic controller, root locus method, linear H_2 control, robust control algorithms such as H_2 and H_∞. Within the scope of the research, three articles were published in international scientific journals indexed in the Scopus and Web of Science databases, and five articles were published in scientific publications recommended by the Committee for Quality Assurance in the Field of Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan for publishing the main results of scientific activity.

Practical significance of the work. Practical significance is characterized by the possibility of using the developed algorithms for controlling the configuration of a formation of satellites, which can subsequently be used for continuous remote sensing of the Earth from geostationary orbit.

Mathematical models, algorithms and results presented in this dissertation work are part of scientific projects to design a motion control system for a formation of satellites for remote sensing of the Earth and can be used in the space industry.

The connection of the work with state scientific programs. This dissertation work was carried out within the framework of the following projects:

– AP05132939 “Control system design of the satellite formation motion for remote sensing of the Earth” grant funding for scientific research from the Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan, 2018 – 2020, No. GR 0118RK00524;

– AP09260469 “Development of a control system able to keep required configuration of a spacecraft formation for the performed mission purposes, taking into account uncertainties caused by external disturbances” grant funding for scientific research from the Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan, 2021 - 2023, No. GR 0121RK00371.

The individual contribution of the doctoral candidate to the preparation of articles.

– N.Kaliyeva, Z.Rakisheva, N.Doszhan*, A.Sukhenko, G.-G.A.Ibrayev, Sh.Nakasuka, and Y.Shabdan. Relative Dynamics and Control of Satellite Formation Flying Representing the Synthetic Aperture Telescope on Geostationary Orbit // Engineered Science. DOI: 10.30919/es1131 (Published Online). 2024, (Scopus, SJR 1.386, Q1, Percentile 98). The author of the dissertation participated in setting the problem, developing the algorithm, carrying out calculations, and preparing the article. Corresponding author.

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In addition, the author of the dissertation published 3 theses at international scientific conferences and symposia. And 1 monograph was published as part of the dissertation work.