UDC 629.7

A. P ALPATOV, Yu. M. HOLDSHTEIN

BALLISTIC PLANNING TECHNIQUE FOR LOW-ORBIT SERVICING MISSIONS WITH LOW CONSTANT THRUST PROPULSION SYSTEMS

Institute of Technical Mechanics
of National Academy of Sciences of Ukraine and State Space Agency of Ukraine
15 Leshko-Popel St., Dnipro 49600, Ukraine; e-mail: aalpatov@ukr.net; jura_gold@meta.ua

The current stage of space exploration is characterized by an increased interest in the development, deployment, and operation of low-orbit satellite constellations (LOSC) for Earth and near-Earth space remote sensing for military and civilian purposes and for global and regional satellite communications. Reusable space launch vehicles have significantly reduced the orbital injection cost. As a result, satellite operators are developing and deploying large-scale LOSCs of various orbital structures with a large number of spacecraft. According to current estimates, more than 70% of all the operating satellites operate in low-Earth orbits (LEOs) at altitudes between 160 km and 2,000 km. Since LEO satellites are generally much cheaper than satellites in geostationary orbits, the possibility of their on-orbit servicing (OOS) has not been the focus of research. However, the use of LEO OOS has prospects for growth. Techniques for ballistic planning of LEO OOS missions have been and are being developed. The disadvantages of approximate techniques include the use of simplified flight dynamics models. Most of the existing exact techniques are based on the use of full mathematical models of flight dynamics and the shooting method to solve the boundary value problem of an orbit transfer. Using the shooting method requires a sufficiently accurate initial guess, which is difficult to determine. To obtain a second approximation, use is mainly made of optimization methods, which do not always find a global minimum. In this regard, there is a need to develop new techniques that would be free from the above disadvantages. The goal of the article is to develop a ballistic planning technique for low-orbit servicing missions with low constant thrust propulsion systems. The technique includes the identification of LEO areas promising for OOS, a mathematical model of the dynamics of perturbed OOS orbit transfers in modified equinoctial orbital elements, and a solution algorithm for the boundary value problem of determining the control parameters of perturbed OOS low-orbit transfers. The problem is solved using methods of statistical analysis, flight dynamics, shooting, genetic optimization, and mathematical simulation. The novelty lies in the identification of LEO areas promising for OOS and the development of a mathematical model of orbit transfer dynamics in modified equinoctial orbital elements and a solution algorithm for determining the control parameters of perturbed OOS low-orbit transfers. The results of the work may be used in the justification and planning of LEO OOS missions and the formulation of requirements for LEO OSS mission propulsion systems.

Keywords: *modified equinoctial orbital elements, genetic optimization algorithm, shooting method, on-orbit servicing, low thrust.*

1. NORAD's space object orbit parameter database. URL: https://www.space-track.org NORAD/ (Last accessed on March 20, 2024).

2. Hastings D. E., Putbrese B. L., La Tour, P. A. When will on-orbit servicing be part of the space enterprise? Acta Astronautica. 2016. V. 127. Pp. 655-666.
https://doi.org/10.1016/j.actaastro.2016.07.007

3. Ho K., Wang H., DeTrempe P. A., du Jonchay T. S. Semi-analytical model for design and analysis of on-orbit servicing architecture. Journal of Spacecraft and Rockets. 2020. V. 57. Iss. 6. Pp. 1-10.
https://doi.org/10.2514/1.A34663

4. Edelbaum T. N. Optimal nonplanar escape from circular orbits. AIAA J. 1971. V. 9. No. 13. Pp. 2432-2436.
https://doi.org/10.2514/3.50047

5. Kechichian J. A. The streamlined and complete set of the nonsingular J2-perturbed dynamic and adjoint equations for trajectory optimization in terms of eccentric longitude. J. Astronaut. Sci. 2007. V. 55. Is. 3. Pp. 325-348.
https://doi.org/10.1007/BF03256528

6. Cerf M. Low-thrust transfer between circular orbits using natural precession, J. Guid. Control Dynam. 2016. V. 39. No. 10. Pp. 2232-2239.
https://doi.org/10.2514/1.G001331

7. Zhang S., Han C., Sun X. New solution for rendezvous between geosynchronous satellites using low thrust J. Guid. Control Dynam. 2018. V. 41. No. 3. Pp. 1-10.

https://doi.org/10.2514/1.G003270

8. Alpatov A. P., Holdstein Yu. M. On the choice of the ballistic parameters of an on-orbit service spacecraft. Teh. Meh. 2019. No. 1. Pp. 25-37.
https://doi.org/10.15407/itm2019.01.025

9. Holdstein Yu. M., Fokov O. A. Optimization of transfers between low orbits with significantly different longitudes of ascending nodes. Teh. Meh. 2022. No. 3. Pp. 63 - 74. (in Ukrainian).
https://doi.org/10.15407/itm2022.03.063

10. Li H., Chen S., Baoyin H. J2-perturbed multitarget rendezvous optimization with low thrust. J. Guid. Control Dynam. 2018. V. 41. No. 3. Pp. 802-808.
https://doi.org/10.2514/1.G002889

11. NASA. Modified equinoctial orbital elements. URL:
https://spsweb.fltops.jpl.nasa.gov/portaldataops/mpg/MPG_Docs/Source%20Docs/EquinoctalElements-modified.pdf (Last accessed on March 20, 2024).

12. Shimane Yu., Gollins N., Ho K. Orbital facility location problem for satellite constellation servicing depots. Journal of Spacecraft and Rockets. Published online on March 25, 2024. URL:
https://arc.aiaa.org/doi/10.2514/1.A35691 (Last accessed on March 20, 2024).

13. Walker M.., Ireland B., Owens J. A set of modified equinocтial orbit elements. Celestial Mechanics. 1985. V. 36. No. 4. Pp. 409-419.
https://doi.org/10.1007/BF01227493

14. Zhang S., Han C., Sun X. New solution for rendezvous between geosynchronous satellites using low thrust. J. Guid. Contr. Dynam. 2018. V. 41. No. 3. Pp. 1397-1406.
https://doi.org/10.2514/1.G003270

15. Han C., Zhang S., Wang X. On-orbit servicing of geosynchronous satellites based on low-thrust transfers considering perturbations. Acta Astronautica. 2019. V. 159. Pp. 658-675.
https://doi.org/10.1016/j.actaastro.2019.01.041

Received on May 13, 2024,
in final form on June 16, 2024