Optimization of Phobos mission with hybrid propulsion returning to the Earth

© I.S. Grigoryev[1], M.P. Zapletin[1,2], A.S. Samokhin[1,2,3], M.A. Samokhina[2,3]

[1]Lomonosov Moscow State University, Moscow, 119991, Russia
[2]Peoples' Friendship University of Russia, Moscow, 117198, Russia
[3]Higher School of Economics, Moscow, 101000, Russia

The article considers the problem of optimizing the spacecraft recovery space flight to Phobos. On the one hand, this task is confined to a real mission to Phobos, which the Russian Federation plans to accomplish in the coming years. On the other hand, the development of techniques for optimizing the spacecraft interplanetary trajectories is the question of present interest. Usually, in such tasks, the circumplanetary legs of trajectory are neglected and there is no end-to-end optimization of the entire mission. The paper shows a technique for constructing Pontryagin extremals in similar problems, taking these features into account, using the example of an expedition to Phobos. The positions of the Earth, Mars and Phobos correspond to the ephemerides DE424 and MAR097. Gravitational fields of the Sun and Mars are considered to be central Newtonian. Spacecraft is equipped with high- and low-thrust engines. The problem of cosmodynamics is formalized as an optimal control task and then it is solved numerically by shooting method. The paper shows the particular constructed trajectories, estimates the possible gain due to using hybrid propulsion instead of only high-thrust engines.

Keywords: *low-thrust, hybrid propulsion, end-to-end optimization, interplanetary flight optimization, spacecraft trajectory optimization, Phobos, flight to Phobos, Phobos mission, Mars mission, cosmodynamics problem*

REFERENCES

[1] Eneev T.M. *Kosmicheskie issledovaniya — Cosmic Research*, 2005, vol. 43, no. 6, pp. 403–407.
[2] *Fobos–Grunt. Proekt kosmicheskoy ekspeditsii.* V 2 tomakh. Tom 1, 2. [Phobos-Grunt. The space mission project. Scientific publication in 2 volumes. Vol. 1, 2]. Moscow, FSUE "Lavochkin Association", 2011, 519 p.
[3] Avduevskiy V.S., Akim E.L., Kremnev R.S., Kulikov S.D. *Kosmonavtika i raketostroenie — Cosmonautics and Rocket Engineering,* 2000, vol. 19, pp. 8–21.
[4] Akim E.L., Zaslavskiy G.S., Morskoy I.M., Ruzskiy E.G. *Astronomicheskiy vestnik — Solar System Research*, 2010, vol. 44, no. 1, pp. 29–40.
[5] Marov M.Ya. *Astronomicheskiy vestnik — Solar System Research*, 2010, vol. 44, no. 1, pp. 3–6.
[6] Galimov E.M. *Astronomicheskiy vestnik — Solar System Research*, 2010, vol. 44, no. 1, pp. 7–16.
[7] Simonov A.V., Morskoy I.M., Stepanyants V.A., Tuchin A.G. *Vestnik FGUP NPO im. S.A. Lavochkina — Bulletin of Lavochkin Association*, 2011, no. 3, pp. 66–73.
[8] Edelbaum T.N. *Journal of the Astronautical Sciences*, 1962, vol. 9, no. 2, pp. 49–69.
[9] Ivanov Yu.N. *Izvestiya AN SSSR. Mekhanika i mashinostroenie — Proceedings of the AS USSR. Mechanics and Mechanical Engineering*, 1964, no. 2, pp. 3–14.

[10] Grigoryev I.S. *Fundamentalnye i prikladnye problemy kosmonavtiki — Fundamental and Applied Problems of Cosmonautics*, 2000, no. 3, pp. 11–18.
[11] Fedotov G.G. *Kosmicheskie issledovaniya — Cosmic Research*, 2001, vol. 39, no. 6, pp. 613–621.
[12] Bolle A., Circi C., Corrao G. *Celestial Mechanics and Dynamical Astronomy*, 2006, no. 106, pp. 183–196. DOI: 10.1007/s10569-009-9250-1 (accessed December 30, 2016).
[13] Akhmetshin R.Z., Beloglazov S.S., Belousova N.S., Glazkov A.I. Optimizatsiya pereletov k asteroidam i kometam KA s kombinirovaniem dvigateley bolshoy i maloy tyagi [Optimization of flights to asteroids and comets of spacecraft with the combination of high- and low-thrust engines]. *Keldysh Institute Preprint*, 1985, no. 144.
[14] An Observation Geometry System for Space Science Missions. *Navigation and Ancillary Information Facility of JPL of NASA*. NASA, 2017, 13 Apr. URL: http://naif.jpl.nasa.gov/naif (accessed April 04, 2017).
[15] *Federal gosudarstvennoe unitarnoe predpriyatie "Opytnoe konstruktorskoe Buro "Fakel". Kharakteristiki statsionarnykh plazmennykh dvigateley* [Federal State Unitary Enterprise "Experimental Design Bureau "Fakel". Characteristics of stationary plasma thrusters]. Available at: http://www.fakel-russia.com/ (accessed December 30, 2016).
[16] Bakhvalov N.S., Zhidkov N.P., Kobelkov G.M. *Chislennye metody* [Numerical methods]. Moscow, BINOM. Knowledge Laboratory Publ., 2008, 636 p.
[17] Grigoryev I.S., Grigoryev K.G. *Kosmicheskie issledovaniya — Cosmic Research*, 2003, vol. 41, no. 3, pp. 307–331.
[18] Grigoryev I.S. *Metodicheskoe posobie po chislennym metodam resheniya kraevykh zadach printsipa maksimuma v zadachakh optimalnogo upravleniya* [Methodical manual on numerical methods for solving boundary value problems of the maximum principle in optimal control problems]. Moscow, the Center for Applied Research at the Faculty of Mechanics and Mathematics of Moscow State University Publ., 2005, 159 p.
[19] Fedorenko R.P. *Vvedenie v vychislitelnuyu fiziku* [Introduction to Computational Physics]. Moscow, MIPT Publ., 1994, 526 p.
[20] Isaev V.K., Sonin V.V. *Zhurnal vychislitelnoy matematiki i matematicheskoy fiziki — Journal of Computational Mathematics and Mathematical Physics,* 1963, vol. 3, no. 6, pp. 1114–1116.
[21] Hairer E., Nørsett S.P., Wanner G. *Solving Ordinary Differential Equations.* Springer-Verlag Publ., 1987 [In Russ.: Hairer E., Nørsett S.P., Wanner G. Reshenie obyknovennykh differentsialnykh uravneniy. Moscow, Mir Publ., 1989, 512 p.].
[22] Bogachev K.Yu. *Praktikum na EVM. Metody resheniya lineynykh system i nakhozhdeniya sobstvennykh znacheniy* [Workshop on a computer. Methods for solving linear systems and finding eigenvalues]. Moscow, Faculty of Mechanics and Mathematics of Moscow State University Publ., 1999, 137 p.
[23] Sukhanov A.A. *Astrodinamika* [Astrodynamics]. Seriya "Mekhanika, upravlenie, informatika" [Series "Mechanics, Control, Informatics"]. Moscow, Rotaprint. IKI RAS Publ., 2000, 202 p.
[24] Samokhin A.S. *Vestnik Moskovskogo universiteta. Seriya 1. Mekhanika. Matematika — Moscow University Mechanics Bulletin,* 2014, no. 2, pp. 62–66.
[25] Grigoryev I.S., Grigoryev K.G. *Kosmicheskie issledovaniya — Cosmic Research*, 2007, vol. 45, no. 6, pp. 1–11.

Grigoryev I.S. (b. 1969), Cand. Sc. (Phys.-Mat.), Associate Professor, Department of Computational Mathematics, Faculty of Mechanics and Mathematics, Lomonosov Moscow State University. e-mail: iliagri@mech.math.msu.su

Zapletin M.P. (b. 1966) graduated from the Faculty of Mechanics and Mathematics of Lomonosov Moscow State University. Cand. Sc. (Phys.-Mat), Associate Professor, Lomonosov Moscow State University, Professor, Peoples' Friendship University of Russia.
e-mail: Zapletin_m@mail.ru

Samokhin A.S. (b. 1989) graduated from the Faculty of Mechanics and Mathematics of Lomonosov Moscow State University. Assistant Lecturer, Department of Computational Mathematics, Faculty of Mechanics and Mathematics, Lomonosov Moscow State University, Senior Lecturer, Peoples' Friendship University of Russia, Lecturer, Higher School of Economics, Leading Specialist, Department of Ballistic Design of Space Systems, Cosmoexport Aerospace Research Agency.
e-mail: SamokhinAlexander@yandex.ru

Samokhina M.A. (b. 1987) graduated from the Faculty of Mechanics and Mathematics of Lomonosov Moscow State University, Senior Lecturer, Peoples' Friendship University of Russia, Lecturer, Higher School of Economics, Leading Specialist, Department of Ballistic Design of Space Systems, Cosmoexport Aerospace Research Agency.
e-mail: kipt35@gmail.com