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Boundary problem solution algorithm for the task of controlled spacecraft motion in irregular gravitational field of an asteroid

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Abstract

The problem of controlled spacecraft motion in vicinity of asteroids is an important flight dynamics task. Solution of the problem consists of gravitational field simulations and control trajectory scheme defininition. We propose to use the model of single gravity points for motion simulation of a spacecraft in an irregular gravitational field of the Eros 433 asteroid. The equations of spacecraft motion are the corresponding equations of the n-body problem. The motion trajectory can be split into a number of from-point-to-point motion parts. Each part can be considered as a two-point Boundary task. The Authors developed a concept of Boundary problem solution based on the Pontryagin's principle and modified Newton's step-by-step approximation method. The Authors developed a special software for the Boundary problem solutions. A boundary task of the controlled spacecraft's transfer between circular orbits from 200 km to 100 km is presented in the paper.

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Keywords: spacecraft; electric propulsion engine; electrospray engine; irregular gravitational field; n-body task; boundary task; asteroid.

1. Introduction

Over the last years, asteroid and comet explorations have become more popular. The reasons for this are: asteroid and comet investigations provide valuable insights into the history of the Universe, asteroids are considered as an important source of resources for commercial and exploration needs and, moreover, as objects that provide operational experience for future space explorations [1].

The spacecraft is usually equipped with an electric propulsion engine that allows manoeuvring in vicinity of asteroids in the long term. While designing spacecraft missions researchers face a problem of controlled motion near asteroids. Control schemes are supposed to be effective in the context of time restriction and fuel consumption. The optimization of low-thrust trajectories is a well-known subject [2], and is performed by using numerical procedures. There are a number of approaches for optimizing a flight trajectory. However, the task becomes complicated because orbital motion about asteroids is highly nonlinear due to inhomogeneities in the irregular gravitational field. Classical theories of motion close to spheroidal bodies cannot be applied as for inhomogeneous bodies the Keplerian forces do not provide a good approximation of the system dynamics [3].

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Nomenclature

α, β	control spacecraft's angles
BsXYZ	barycentric rectangular coordinate system
IsP	specific impulse of electrospray engine
$\mathbf{\Psi}$	conjugate variables vector
G	gravity constant
m	mass of gravitate point system
m_{sv}	mass of spacecraft
$\mathbf{P}$	propulsive force vector
$\mathbf{r}_{sv}$	radius vector of spacecraft's position
$\mathbf{r}_{SUN}$	radius vector of Sun's position
$\mathbf{\Delta}$	radius vector of Sun's position with respect to a spacecraft's position
δ	Boolean function (0 or 1)
τ	fuel consumption
μ	gravity parameter $\mu = Gm$
U	gravitational potential

The paper considers the spacecraft's trajectory as a superposition of separate regions. Each region is a trajectory segment that can be defined as a two-point Boundary task: position of start point and destination point are known, power plant characteristics are also known, the control program is supposed to be identified. Authors developed the optimization scheme of controlled spacecraft's motion based on the Pontryagin's principle and Newton's approximation method. It is proposed considering the task of the transfer between circular orbits for the motion near asteroid Eros in the paper. The choice of the cosmic body is explained by the shape of the asteroid. The bulk of the asteroid is a dumbbell that creates a non-spherical and unstable in time gravitational field.

2. Gravitational field model

The asteroid Eros 433 is considered in the paper with the physical properties [4]:

- size is 34.4x11.2x11.2 km,
- mean diameter is 16.8 km,
- mass is $\approx 6.69 \cdot 10^{15}$ kg,
- rotation period is 5.27 hours.

Authors propose the barycentric model of the gravitational potential as the model of the gravitational potential of Eros 433. Therefore, it was decided to consider the gravitational field of the asteroid as a superposition of N-gravitate points. A number of the points and theirs positions determine accuracy of the model [5]:

$$m_t = \sum_{i=1}^{n} m_i \to \mathbf{U}(\mathbf{r}_{SV}) = \sum_{i=1}^{n} \mathbf{U}_i(\mathbf{r}_i) = G \cdot \sum_{i=1}^{n} \frac{m_i}{\sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}} \tag{1}$$

The model of Eros 433 gravitational field is the superposition of two mass points: $4.356 \cdot 10^{15}$ kg, $2.334 \cdot 10^{15}$ kg, which are rotating around the single barycentre with an angular velocity $5.6 \cdot 10^{-4}$ rad/sec. Precise values of masses and the distance between two gravity points were calculated by the direct search method (Fig.1).