UDC 629.78 DOI: 10.18698/0236-3941-2020-2-4-16

ANALYSIS OF THE ORBITAL APPROACH DYNAMICS OF THE SPACE DEBRIS COLLECTOR TO THE FRAGMENT OF DEBRIS BY THE METHOD OF THRUST REVERSAL WITH INTERRUPTION

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Abstract

The debris collector and a debris fragment move along random noncoplanar orbits in the altitude range of 400–2000 km. The thrust of the promising engine is 5000–25 000 N, the specific impulse of the promising fuel is not lower than 20 000 m/s. The remaining fuel after approach is not less than the specified. The debris collector undocks from the base station, transfers from its orbital plane to the debris fragment orbital plane, performs phasing, approaches the fragment, grabs it and returns to the base station. The paper considers only the stage of orbital approach. The duration of the entire flight mission is limited to one day. The phasing time is insufficient, therefore, at the start time of the orbital approach, the distance to the target is ~ 100 km, the relative velocity is ~ 1 km/s. On the other hand, for reliable and safe grabbing of a debris fragment, it is necessary to provide a distance of ~ 1 m and a relative velocity of ~ 1 m/s. It is shown that this can be achieved by approach using the method of thrust reversal with interruption. An effective algorithm of approach with target is proposed. An analysis of the orbital approach dynamics was performed by joint numerical integration of the orbital motion equations of the debris collector and the debris fragment by the 4th-order Runge — Kutta method. Approach is performed in 6 cycles. In each cycle, the engine turns on three times. Two cycles are performed by sustainer engines, four cycles are performed by auxiliary engines of lower thrust. The fuel depletion and the non-sphericity of the Earth's gravitational field according to the 2nd zonal harmonic are taken into account. Calculation example is considered. Convergence

Keywords

Space debris collector, debris fragment, orbital approach, thrust reversal

estimates of the integration procedure by the resultant distance to the target and the resultant relative velocity are given. Resultant orbital approach is oscillation process with heavy damping. Damping is ensured by multiple firings of the sustainer (auxiliary) engine

Received 13.05.2019
Accepted 16.10.2019

Introduction. The requirements for the approach of two bodies on orbit are formulated in [1], general issues of planning trajectories of debris collection in [2]. It should be noted that similar problems arise in space interception tasks. So, a project of a space interceptor with a permanent space deployment was considered in [3]. The problem of a target interception from the Earth was considered in [4, 5]. The effect of aerodynamic heating on the approach of bodies during low-orbit interception is studied in [4]. An algorithm that generalizes the well-known method of proportional approach is proposed in [5].

As a rule, to save resources, these orbital transfers are not time-limited. In this work, the debris collector and a debris fragment move along random non-coplanar orbits in the altitude range of 400–2000 km. The debris collector undocks from the base station, transfers from its orbital plane to the debris fragment orbital plane, performs phasing, approaches the fragment, grabs it and returns to the base station. The duration of the flight mission is one day.

The possibility of debris collection from near Earth orbit is largely determined by the energy capabilities of the spacecraft propulsion system. Traditional liquid-propellant rocket engines create a fairly high thrust, but require a lot of fuel [6–8]. So, the specific impulse of the most common UDMH + NTO pair of fuel components is approximately 3000 m/s. On the other hand, solar thermal propulsion systems, electric jet engines, nuclear engines have a high specific impulse of up to 100 000 m/s, but provide extremely low thrust of the order of 10 N [9–14]. This paper discusses a promising propulsion system based on new physical principles with a thrust of 5000–25 000 N. Specific impulse of promising fuel is at least 20 000 m/s.

For reliable grabbing of a debris fragment it is necessary to fly up to it at a distance of ~ 1 m with a relative velocity of ~ 1 m/s. A transfer of such accuracy cannot be calculated by considering a model of an orbit composed of pieces of standard curves. It is necessary to integrate the equations of the joint orbital motion of two bodies in Cartesian coordinates taking into account: 1) the non-sphericity of the Earth's gravitational field, 2) fuel depletion. Important results on the short-range guidance and berthing of spacecrafts were obtained in [15–17]. Effective techniques for motion control vehicles with finite thrust in the noncentral gravitational field of the Earth were developed in [18, 19]. In this paper, the non-sphericity of the gravitational field is taken into account by expanding the perturbed geopotential in a series of spherical functions with retention of the 2nd zonal harmonic [20]. Actual problems of numerical integration of the orbital motion equations are considered in [21–23]. So, a detailed comparative analysis of numerical methods for solving the Cauchy problem with initial conditions for orbital transfers is given in [21]. The list of references given in [21] contains about 100 works of domestic and foreign researchers. This work is freely distributed on the Internet. It indicates the need to create special numerical algorithms for modeling long transfers of the order of 1000 days. This article discusses a short-term mission during one day. It is shown that under the given conditions, the well-known 4th-order Runge — Kutta method [24] gives acceptable integration accuracy.

Orbital motion equations. The orbital motion equations of the space debris collector and the debris fragment in Cartesian coordinates are considered together. Objects do not interact with each other, while the movement of one object is organized taking into account the movement of another object. Due to the non-sphericity of the Earth (taking into account the 2nd zonal harmonic of the expansion of the perturbed geopotential of the Earth in a series of spherical functions [17], the equations of the joint orbital motion of two bodies have the following form:

$$\begin{aligned}
\ddot{x}_c &= -\mu x_c / r_c^3 - 3\mu J_2 a_e^2 (5 x_c z_c^2 / r_c^2 - x_c) / 2 / r_c^5 + a_x;\\
\ddot{y}_c &= -\mu y_c / r_c^3 - 3\mu J_2 a_e^2 (5 y_c z_c^2 / r_c^2 - y_c) / 2 / r_c^5 + a_y;\\
\ddot{z}_c &= -\mu z_c / r_c^3 - 3\mu J_2 a_e^2 (5 z_c^3 / r_c^2 - 3 z_c) / 2 / r_c^5 + a_z;\\
\ddot{x}_f &= -\mu x_f / r_f^3 - 3\mu J_2 a_e^2 (5 x_f z_f^2 / r_f^2 - x_f) / 2 / r_f^5;\\
\ddot{y}_f &= -\mu y_f / r_f^3 - 3\mu J_2 a_e^2 (5 y_f z_f^2 / r_f^2 - y_f) / 2 / r_f^5;\\
\ddot{z}_f &= -\mu z_f / r_f^3 - 3\mu J_2 a_e^2 (5 z_f^3 / r_f^2 - 3 z_f) / 2 / r_f^5,
\end{aligned} \tag{1}$$

where x_c, y_c, z_c and x_f, y_f, z_f are Cartesian coordinates of the debris collector (*c*) and the debris fragment (*f*); $\mu = 3.9860044 \cdot 10^{14}$ m^3/s^2 is Earth's gravitational constant; $r_c = \sqrt{x_c^2 + y_c^2 + z_c^2}$, $r_f = \sqrt{x_f^2 + y_f^2 + z_f^2}$ are modules of radius vectors $\vec{r}_c$ and $\vec{r}_f$ of the debris collector and the debris fragment; $a_e = 6\,378\,136$ m is Earth's average radius; $J_2 = 1082.636023 \cdot 10^{-6}$ is coefficient of the 2nd zonal harmonic of the expansion of the perturbed geopotential of the Earth in a series of spherical functions; a_x, a_y, a_z are Cartesian components of the debris collector acceleration due to (multiple) engine firings during the orbital approach of the debris collector with the debris fragment. It is accepted that to give out an impulse the vehicle turns around instantly. The inertia of the vehicle rotation is not taken into account. The fragment of debris does not have a propulsion system.

The system of equations (1) in Cartesian coordinates is integrated with the specified initial conditions by the 4th-order Runge — Kutta method with automatic step selection. Equations (1) are integrated with double precision. As a rule, the initial conditions are specified as 6 parameters of the initial osculating elliptical orbit $a, e, \Omega, \omega, i, \upsilon$, where a is semimajor axis, e is eccentricity, Ω is longitude of ascending node, ω is perigee argument, i is orbit inclination, υ is true anomaly. The indicated six parameters of the ellipse are converted into three Cartesian coordinates of the body x, y, z and three Cartesian components of its velocity $\dot{x}, \dot{y}, \dot{z}$. These direct and inverse transforms are well known [17].

Algorithm of approach with thrust reversal. Approach is carried out in several cycles. The initial cycle is shown in Fig. 1. The remaining cycles are performed similarly. Each cycle consists of three steps. When approach begins, the debris collector is at point A_0, the debris fragment is at point B_0. At this instant of time, the position of the debris fragment is determined by the distance vector $\vec{d}_0$. The relative velocity is determined by the vector $\Delta\vec{V}_0$. At step no. 1 (segment A_0A_0', Fig. 1), the relative velocity is reset to zero.

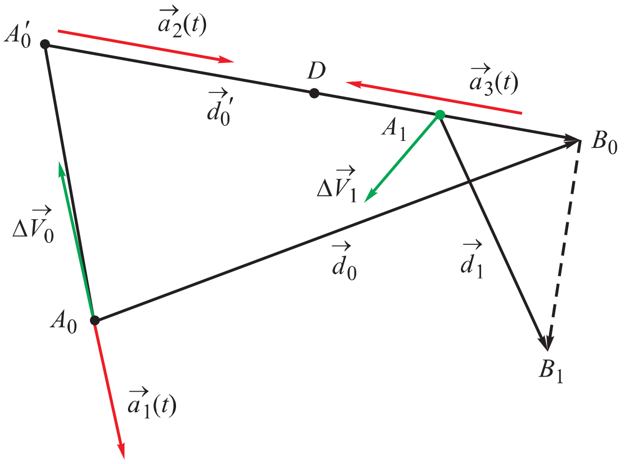

Fig. 1. Initial approach cycle by the method of thrust reversal with interruption

At that, the distance may increase. Let t_1 be the time of transfer from point A_0 to point A_0' (step no. 1), t_2 be the time of transfer from point A_0' to point D

(step no. 2), t_3 be the time of transfer from point A_0' to point B_0 (step no. 2 and step no. 3 together). Let $t_2 = \alpha t_3$, $0.5 \le \alpha \le 1.0$, $\alpha = 0.5$ is with uniformly accelerated motion, when fuel is not depleting and the mass of the debris collector is not changing. At point D, the direction of the acceleration vector (engine thrust vector) is reversed. This is the thrust reversal. Due to reversal, the relative velocity of the bodies at point B_0 should be zeroed. But this does not happen: the debris fragment moves in orbit; it changes position to point B_1. At point A_1, the distance to the debris fragment begins to grow. As soon as the distance begins to grow, the cycle is interrupted. Point A_1 is the start point of a new approach cycle of the debris collector with the debris fragment. At that $\vec{d}_1$ is a new distance vector, $\Delta\vec{V}_1$ is a new relative velocity vector. The initial data for the subsequent cycle is the calculation result of the previous one.

The module of the debris collector acceleration vector in general form is as follows:

$$a(t) = F/(b + ct), \tag{2}$$

where $F = F_{1,\,2}$ is thrust of the sustainer (auxiliary) engine; $b = m_{structure} + m_{fuel}$; $m_{structure}$ is debris collector structural mass; m_{fuel} is fuel remaining at engine firing at this step of the approach cycle; γ is specific impulse of promising fuel; $c = -F/\gamma < 0$ is value equal (in absolute value) to the fuel consumption in the engine per second. At step no. 1 of the initial cycle:

$$\Delta\vec{V}_0 = (\dot{x}_c - \dot{x}_f,\ \dot{y}_c - \dot{y}_f,\ \dot{z}_c - \dot{z}_f) = (\Delta V_{0x},\ \Delta V_{0y},\ \Delta V_{0z});$$

$$\Delta V_0 = \left|\Delta\vec{V}_0\right| = \sqrt{\Delta V_{0x}^2 + \Delta V_{0y}^2 + \Delta V_{0z}^2}; \tag{3}$$

$$\cos\alpha_{vx} = \Delta V_{0x}/\Delta V_0;\ \cos\alpha_{vy} = \Delta V_{0y}/\Delta V_0;\ \cos\alpha_{vz} = \Delta V_{0z}/\Delta V_0.$$

From Fig. 1 it follows that the negative acceleration $\vec{a}_1(t) \,||\, (-\Delta\vec{V}_0)$, therefore

$$\vec{a}_1(t) = (-a_1(t)\cos\alpha_{vx},\ -a_1(t)\cos\alpha_{vy},\ -a_1(t)\cos\alpha_{vz}) = (a_x,\ a_y,\ a_z), \tag{4}$$

where, by analogy with (2), $a_1(t) = \left|\vec{a}_1(t)\right| = F_1/(b + ct)$. The components of the acceleration vector (4) at step no. 1 are substituted into the system of equations (1).

To determine the duration t_1 of engines' firing at step no. 1 of the initial cycle (taking into account fuel depletion), we have:

$$V_1(t) = \int_0^r a_1(t)\,dt = \int_0^t F/(b + ct)dt = F\ln(1 + ct/b)/c;$$

$$V_1(t_1) = \Delta V_0,$$

from which

$$t_1 = b\,(1 - \exp(\Delta V_0 c\,/\,F))\,/\,c. \qquad (5)$$

The velocity vector $\Delta\vec{V}_0(t)$ (3) of the debris collector relative to the debris fragment and the acceleration vector $\vec{a}_1(t)$ (4) are refined at each integration step on the segment A_0A_0'. At that, the duration of engine firing t_1 (5) is calculated once at point A_0 and remains unchanged.

Consider steps no. 2 and no. 3 of the approach cycle. Time is counted from the point A_0'. Velocity increments due to engine firing, taking into account fuel depletion:

$$V_2(t) = \int_0^t a_2(t)dt = F\ln(1 + ct\,/\,b)\,/\,c; \qquad (6)$$

$$V_3(t) = \int_0^{\alpha t_3} a_2(t)dt + \int_{\alpha t_3}^{t} (-F)\,/\,(b + ct)\,dt =$$

$$= 2F\ln(1 + c\alpha t_3\,/\,b)\,/\,c - F\ln(1 + ct\,/\,b)\,/\,c\,. \qquad (7)$$

At point B_0, the debris collector should stop relative to the debris fragment. The total velocity increment on steps no. 2 and no. 3 is equal to zero

$$V_3(t_3) = 0.$$

Consequently,

$$2\ln(1 + c\alpha t_3)\,/\,b = \ln(1 + ct_3\,/\,b).$$

From this follows the quadratic equation:

$$\alpha^2 + 2b\,/\,(ct_3)\,\alpha - b\,/\,(ct_3) = 0;\;\; \alpha = \frac{-b + \sqrt{b\,(b + ct_3)}}{ct_3};\;\; 0.5 \le \alpha \le 1.0. \qquad (8)$$

The second root of this quadratic equation does not make sense.

Suppose $u = ct_3\,/\,b$. Given the expressions (6), (7), the total path on steps no. 2 and no. 3:

$$s(t_3) = \int_0^{\alpha t_3} V_2(t)\,dt + \int_{\alpha t_3}^{t_3} V_3(t)\,dt =$$

$$= 2Fb[(1 + \alpha u)\ln(1 + \alpha u) - \alpha u]\,/\,c^2 + 2F\ln(1 + \alpha u)\,t_3(1 - \alpha)\,/\,c -$$

$$- Fb[(1 + u)\ln(1 + u) - u]\,/\,c^2. \qquad (9)$$

The total duration t_3 of sustainer (auxiliary) engine firing on step no. 2 and step no. 3 is found taking into account (8) the iterative procedure for the residual:

$$\frac{d_0' - s(t_3)}{d_0'} \to 0, \tag{10}$$

where

$$\begin{gathered}
\vec{d}_0' = (x_f - x_c',\ \ y_f - y_c',\ \ z_f - z_c') = (d_{0x}',\ \ d_{0y}',\ \ d_{0z}');\\
d_0' = \left|\vec{d}_0'\right| = \sqrt{d_{0x}'^2 + d_{0y}'^2 + d_{0z}'^2}; \\
\cos\alpha_{dx} = d_{0x}' / d_0'; \quad \cos\alpha_{dy} = d_{0y}' / d_0'; \quad \cos\alpha_{dz} = d_{0z}' / d_0'.
\end{gathered} \tag{11}$$

The characteristic curve of the residual (10) dependence on t_3 is given in Fig. 2.

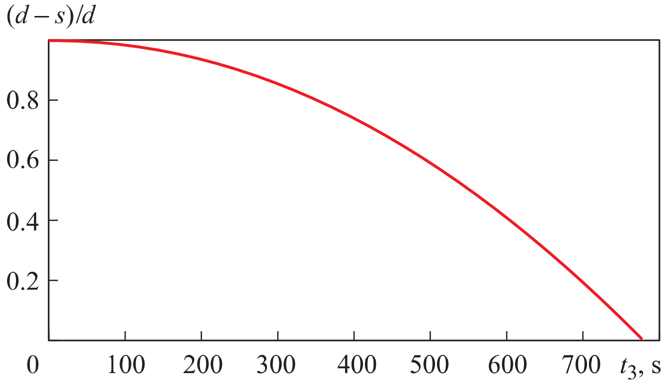

Fig. 2. The characteristic curve of the residual (10) dependence on t_3

At point D (Fig. 1), the thrust reversal takes place. Therefore

$$\begin{gathered}
\vec{a}_2(t) \parallel \vec{d}_0'; \quad \vec{a}_3(t) \parallel (-\vec{d}_0');\\
\vec{a}_2(t) = (a_2(t)\cos\alpha_{dx},\ \ a_2(t)\cos\alpha_{dy},\ \ a_2(t)\cos\alpha_{dz});\\
\vec{a}_3(t) = (-a_3(t)\cos\alpha_{dx},\ \ -a_3(t)\cos\alpha_{dy},\ \ -a_3(t)\cos\alpha_{dz}).
\end{gathered} \tag{12}$$

The components (12) of the acceleration vectors $\vec{a}_2(t)$, $\vec{a}_3(t)$ are substituted into the orbital motion equations (1). The displacement vector $\vec{d}_0'$ (11) and acceleration vectors $\vec{a}_2(t)$, $\vec{a}_3(t)$ (12) are refined at each integration step on the segment $A_0'B_0$ (Fig. 1). The duration of engine firing t_3 (5) is determined once by the iterative procedure (10) at point A_0' and remains unchanged. If at step no. 3 the calculation program detects an increase in the distance d_0' instead of its expected decrease, then the current approach cycle is interrupted (at point A_1, Fig. 1).

Calculation example. Initial data: structural mass $m_{structure}$ = 1000 kg, initial mass of fuel of the debris collector 2000 kg, the moment of approach beginning 35 637.500 s; fuel mass at the moment of approach beginning m_{fuel} = = 1292.057 kg, specific impulse of prospective fuel γ = 30 000 m/s, thrust of a promising sustainer propulsion system F_1 = 5000–25 000 N, thrust of an auxiliary propulsion system $F_2 = F_1 / 2$; initial distance to the debris fragment d_0 = 162 952.712 m; the initial velocity of the debris collector relative to the debris fragment ΔV_0 = 709.078 m/s. Equations (1) of the joint orbital motion of bodies are integrated with double precision. The initial conditions for the integration of the equations of the debris fragment orbital motion are given in Table 1.

Table 1

Initial conditions for the integration of the equations of the debris fragment orbital motion (1) at the moment of approach beginning 35 637.500 s

Initial values of the Cartesian coordinates and components of the debris fragment velocity vector	Initial values of the parameters of the osculating elliptical orbit
Orbit altitude ~ 2000 km, orbit inclination ~ 28°	
x_{f0} = – 441 346.4319433745 m	a_{f0} = 8 375 570.432312139 m
y_{f0} = – 7 421 649.898237308 m	e_{f0} = 0.002215688778602025
z_{f0} = – 3 864 039.014819950 m	Ω_{f0} = 188.6005006433259 deg
$\dot{x}_{f0}$ = 6870.025978835349 m/s	ω_{f0} = 179.8709088267034 deg
$\dot{y}_{f0}$ = – 84.304942150274900 m/s	i_{f0} = 27.98371339054505 deg
$\dot{z}_{f0}$ = – 590.178619154929600 m/s	υ_{f0} = 100.5555493868468 deg

In Fig. 3, 4 it is shown that the approaching process of bodies by distance and relative velocity is oscillatory in nature with heavy damping. The damping is due to application of thrust reversal algorithm with interruption. The approaching process consists of 6 cycles: 2 cycles with sustainer engines and 4 cycles with auxiliary engines of lower thrust. From the table 2 it follows that the resultant distance to the fragment is ~ 1 m, the resultant relative velocity is ~ 2 m/s. It should be noted that with a decrease in engine thrust, the approach accuracy increases (Fig. 5), and an increase in accuracy is accompanied by a significant increase in the approach duration and additional fuel consumption (Fig. 6). The total approach duration for the considered calculation cases varied from 500 to 1500 s (approximately 1/10 of a revolution).

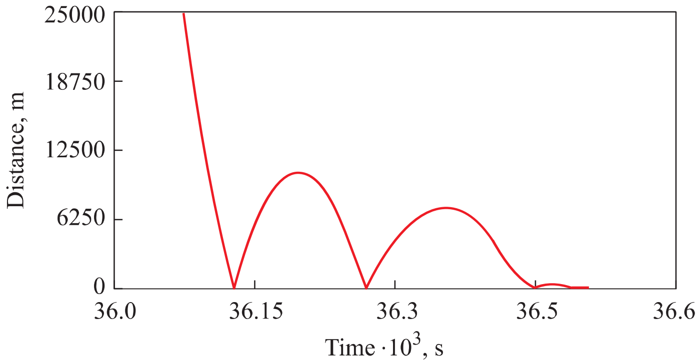

Fig. 3. The approaching process by the distance at F_1 = 10 000 N (time — in thousands of s)

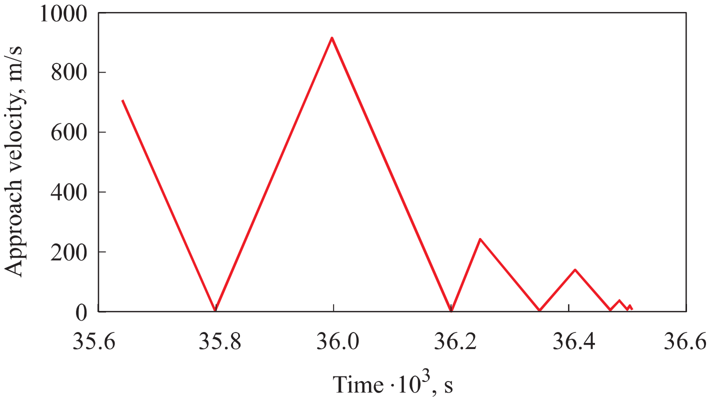

Fig. 4. The approaching process by the relative velocity at F_1 = 10 000 N (time — in thousands of s)

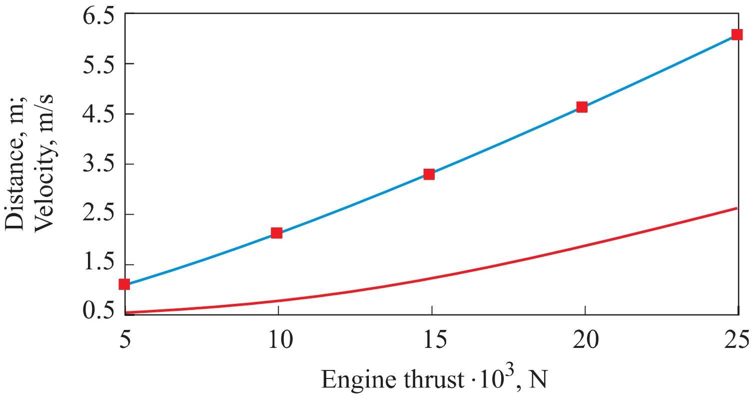

Fig. 5. Dependence of the resultant distance (red curve) and the resultant relative velocity (blue curve) on the engine thrust

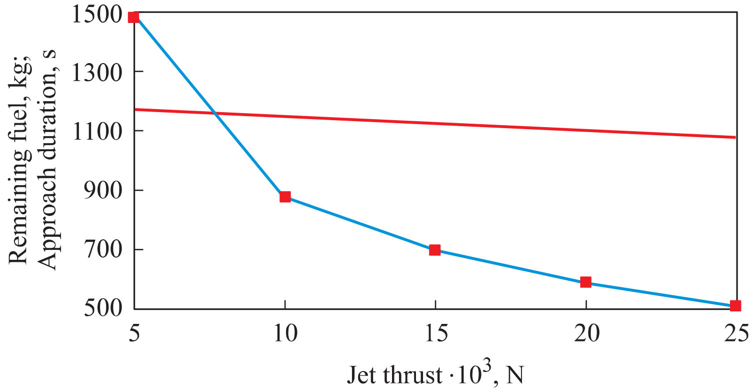

Fig. 6. Dependence of the approach duration (blue curve) and the mass of the remaining fuel (red curve) on the engine thrust

Of great interest is the convergence analysis of the orbital motion equations (1) integrating procedure by the fourth-order Runge — Kutta method with automatic step selection. The results of the convergence analysis are given in Table 2 at the time of approach completion. If the increment of the phase coordinates at the integration step exceeds a predetermined threshold value, then the integration step is divided by 3. At that, the accuracy of the calculation increases, but the integration time of the equations rapidly increases. From the Table 2 it follows that to solve the problem, the 4th-order Runge — Kutta method is applicable.

Table 2

The convergence of numerical integration of the orbital motion equations by the 4th-order Runge — Kutta method by distance and relative velocity at the time of approach completion

The threshold value of the increment of phase coordinates at the integration step (m, m/s)	The resultant distance to the debris fragment at time 36 508.301 s	The resultant velocity of the debris collector relative to the debris fragment at time 36 508.301 s
1000	0.6528346384948821 m	1.807193579274474 m/s
100	0.7866356254479596 m	2.062311565709974 m/s
10	0.7968067652386960 m	2.061281651160472 m/s
1	0.8037243611832358 m	2.069899492764863 m/s

Conclusions. 1. The orbital approach of the space debris collector with a debris fragment can be provided by the method of thrust reversal with interruption. At that, the approach accuracy by distance ~ 1 m, the approach accuracy by relative velocity ~ 2 m/s.

2. The orbital approach of bodies is an oscillatory process with heavy damping. The damping is ensured by multiple firing of the sustainer propulsion system, as well as the auxiliary propulsion system of lower thrust.

3. To integrate the equations of joint orbital motion of two bodies, taking into account fuel depletion and the non-sphericity of the Earth's gravitational field (during one day), the 4th-order Runge — Kutta method can be used. The convergence estimates of the integration procedure by distance and relative velocity are given.

Translated by A.E. Kurnosenko

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Please cite this article as:

Arinchev S.V. Analysis of the orbital approach dynamics of the space debris collector to the fragment of debris by the method of thrust reversal with interruption. *Herald of the Bauman Moscow State Technical University, Series Mechanical Engineering*, 2020, no. 2, pp. 4–16. DOI: https://doi.org/10.18698/0236-3941-2020-2-4-16