Simulation of Earth’s Protection by Kinetic Interceptor from Asteroid Hazard

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Abstract. The present work is devoted to the Earth’s protection from asteroid danger, namely, the use of the kinetic interceptor - a spacecraft, which by means of collision repels an asteroid from a dangerous orbit. The parameters of near-Earth asteroids are revealed. Mathematical model of the control movement of all bodies (the Earth, the Sun, the asteroid, the spacecraft), the control program and software package (Delphi 7) for the simulation and visualization of the trajectories are designed.

1. Introduction

An asteroid collision with the Earth is an accident that is unlikely to occur but can be by large-scale catastrophic consequences. The consequences of an asteroid collision with our planet can be extremely devastating. Thus, certain preventive measures should be taken.

In recent years the problem of the asteroid hazard (safety) has been discussed at many conferences and described in many books [2, 3, 4, 5]. In particular, the problem of the span of the asteroid 99942 Apophis on the threatening the Earth distance in 2029 was widely discussed in papers [2, 3].

The study of the asteroid hazard covers several areas. First of all, there are the detecting of hazardous near-Earth asteroids (NEA), and the determination of their orbits. Currently there are several national programs of optical observation of these bodies (NASA, LINEAR, ESA). We believe that with the help of these programs we can identify the majority of such bodies with sizes of kilometers or more [2, 6]. A number of studies and projects consider countermeasures from heavenly aliens – changing their orbits or breaking them into small pieces, burning up in the atmosphere [1].

The importance of overcoming the asteroid danger at present is undoubted and the development of measures for its prevention should be one of the primary tasks to be solved by the mankind in the 21st century.

Huge research work on the study of asteroids and their trajectories was conducted. So, for example, in 1975, Clark R. Chapman, David Morrison and Ben Zellner developed a classification system for asteroids, based on the color indexes, albedo, and the characteristics of the spectrum of reflected sunlight [7].

Also, the researchers divided all the asteroids currently existing in to four main categories, named after the most famous representatives of each category: 1221 Amur, 1862 Apollo, and 2062 Aton, 163693 Atira [8].

One of the most important developments research works has been the qualitative scale of asteroids and comets assessment risk of collision with the Earth by the American astronomer R. Binzel. The Torino scale consists of ten items.

In accordance with the scale, asteroids and other celestial bodies are classified (based on their size and relative velocity) according to the degree of threat to Earth [10].
In different centuries a variety of options for addressing asteroid threats, were proposed such as the deflection of asteroids with dangerous orbits using the kinetic interceptor, the mirror system, the use of repaints of the asteroid white, the use of nuclear weapons, solar sails, carbon networks, and the gravitational tug of the spacecraft [9,11].

The aim of our work is to study the method for changing the trajectory of the potentially hazardous asteroid with the use of kinetic interceptor. This method allows to conduct a controlled deflection of the asteroid from a dangerous trajectory without the use of complex and reliable methods for the capture of a rotating asteroid.

2. Asteroid Hazard System Model

2.1 Simulation of a system for protecting the Earth from the asteroid hazard by kinetic interceptor

One of the methods for diverting asteroids with dangerous orbits is the collision with a kinetic interceptor.

This method can be implemented, when the asteroid is still far from the Earth. One way to change its momentum can be achieved by the spacecraft.

The analysis of the threats deviation conducted in 2007 by NASA proves:

The Non-nuclear kinetic interceptor to be the most developed method. That can be used in cases against small near-earth objects consisting of a solid [12].

The European space Agency is already conducting a preliminary study of the possible space flight in which the technology will be tested. The program called "Don Quijote" is a designed mission to repel an asteroid threat [14]. The team of the European Agency, the Advanced Concepts Team, theoretically proved that the reflection of the asteroid (99942) Apophis can be produced by sending a simple spacecraft weighing less than a ton for the ram of this object [14].

If we consider physical process, the change in the trajectory of the asteroid will be due to the law of conservation of momentum:

\[ m_{ast} \cdot \vec{V}_{ast}(t_1) + m_{ki} \cdot \vec{V}_{ki}(t_1) = (m_{ast} + m_{ki}) \cdot \vec{V}_{ast}(t_2), \]

when

- \( m_{ast} \) and \( m_{ki} \) - the mass of the asteroid and kinetic interceptor,
- \( \vec{V}_{ast} \) and \( \vec{V}_{ki} \) - the speed of the asteroid and the kinetic interceptor,
- \( t_1 \) and \( t_2 \) - orbital trip time - before the collision with the kinetic interceptor (stage 1) and after to the collision with the kinetic interceptor (stage 2).

To simulate the process of trajectory change of potentially hazardous asteroid we developed a mathematical model of motion of three interrelated bodies (the asteroid, the spacecraft, the Earth) in the scope of the heliocentric coordinate system [15]. The trajectory of the asteroid changes with the directional thrust of the asteroid by kinetic interceptor.

The model of the motion of these bodies relative to the Sun is represented by Formulae (1-17).

Figure 1. The circuit arrangement of bodies and designations in the method to prevent the asteroid hazard by using a kinetic interceptor.
The arrangement of bodies and symbols in a method of preventing asteroid threats by the kinetic interceptor is presented in Figure 1 [15].

\[ \frac{dx_1}{dt} = V_{x1}, \quad \frac{dy_1}{dt} = V_{y1}, \quad \frac{dz_1}{dt} = V_{z1}, \]
\[ \frac{dx_2}{dt} = V_{x2}, \quad \frac{dy_2}{dt} = V_{y2}, \quad \frac{dz_2}{dt} = V_{z2}, \]
\[ \frac{dx_3}{dt} = V_{x3}, \quad \frac{dy_3}{dt} = V_{y3}, \quad \frac{dz_3}{dt} = V_{z3}, \]
\[ \frac{dx_4}{dt} = V_{x4}, \quad \frac{dy_4}{dt} = V_{y4}, \quad \frac{dz_4}{dt} = V_{z4}, \]
\[ \frac{dV_{x1}}{dt} = -G \frac{m_2}{|r_1|^3} (x_1-x_4), \]
\[ \frac{dV_{y1}}{dt} = -G \frac{m_2}{|r_1|^3} (y_1-y_4), \]
\[ \frac{dV_{z1}}{dt} = -G \frac{m_2}{|r_1|^3} (z_1-z_4), \]
\[ \frac{dV_{x2}}{dt} = -G \frac{m_3}{|r_2|^3} (x_2-x_4), \]
\[ \frac{dV_{y2}}{dt} = -G \frac{m_3}{|r_2|^3} (y_2-y_4), \]
\[ \frac{dV_{z2}}{dt} = -G \frac{m_3}{|r_2|^3} (z_2-z_4), \]
\[ \frac{dV_{x3}}{dt} = -G \frac{m_3}{|r_2|^3} (x_3-x_1), \]
\[ \frac{dV_{y3}}{dt} = -G \frac{m_3}{|r_2|^3} (y_3-y_1), \]
\[ \frac{dV_{z3}}{dt} = -G \frac{m_3}{|r_2|^3} (z_3-z_1), \]
\[ \frac{dV_{x4}}{dt} = -G \frac{m_3}{|r_2|^3} (x_4-x_2), \]
\[ \frac{dV_{y4}}{dt} = -G \frac{m_3}{|r_2|^3} (y_4-y_2), \]
\[ \frac{dV_{z4}}{dt} = -G \frac{m_3}{|r_2|^3} (z_4-z_2), \]
\[ m_1 - \text{the mass of the asteroid}, \]
\[ m_2 - \text{the mass of the Sun}, \]
\[ m_3 - \text{the mass of the kinetic interceptor}, \]
\[ m_4 - \text{the mass of the Earth}, \]
\[ r_1 = (x_1, y_1, z_1)^T - \text{the radius-vector of the asteroid}, \]
\[ r_2 = (x_2, y_2, z_2)^T - \text{the radius-vector of the Sun}, \]
\[ r_3 = (x_3, y_3, z_3)^T - \text{the radius-vector of the kinetic interceptor} \]
\[ r_4 = (x_4, y_4, z_4)^T - \text{the radius-vector of the Earth}, \]
\[ a = (a_x, a_y, a_z)^T - \text{the acceleration from the thrust of the spacecraft}, \]
\[ \alpha - \text{second flow of the working fluid}. \]

3. The simulation results
We have developed a software package (Delphi VII) to study and visualize the asteroid motion before the collision and after changing the trajectory by the kinetic interceptor. The software package allows to specify the required characteristics of the space craft and select from the list the required asteroids (Figure 2). The software package helps to set the angle of the trajectory of the spacecraft, the launch date of the spacecraft from Earth and calculate the end date of the mission. The software package permits to calculate two stages of orbital motion - before the collision with kinetic interceptor and after
the collision with kinetic interceptor, make a comparative analysis of the deviation of the trajectory from the Earth.

Figure 2. Structure of the software complex.

The initial data for the program complex are the design parameters of the planets, asteroid and spacecraft, its phase coordinates [15], control laws. The software package provides: the ability to simulate and display the heliocentric motion of a single kinetic interceptor, the ability to form a given trajectory using a set of locally optimal controls, the ability to save the data in text files of the spacecraft simulation results. The program complex uses the equations of motion (1-17) and the control laws corresponding to the chosen method of overcoming the asteroid danger. The results of the program complex are: the trajectory of the flight; graphs of changes in the orbital elements and spacecraft control laws; table with the simulation results, which is displayed in a text file.

3.1. The simulation of asteroid hazard prevention by kinetic interceptor

We received numerical simulation of the bodies motion by the Runge-Kutta Fourth Order method. The software package allows to visualize the trajectory of motion of bodies system [13]. When modelling the orbit changes, we applied the following parameters of the heavy space vehicle

\[ m_3 = 10 \cdot 10^3 \text{ kg}, \quad \lambda = 87^\circ, \quad a = 3.75 \cdot 10^4 \text{ kg/s}, \quad P = 25N \]

Launch date: 15.09.2020.
End date: 3.08.2021.

Figure 3 we can see that the software package was able to simulate and visualize the deviation of the asteroid Apophis from a dangerous orbit. After the collision, the movement of the kinetic interceptor is not considered. At that time, as Apophis manages to make one revolution and is rejected with the threat of the orbit, the Earth completes its first round. Consequently, it can be concluded that the kinetic interceptor method is applicable to the removal of an asteroid hazard.

Figures 4-7 show graphs of the dependence of the displacements and velocities of the asteroid Apophis and the spacecraft. According to the charts, it is possible to make a comparative analysis of the movements and velocities of the asteroid and the kinetic apparatus before and after the shock. The red line simulates the collision boundary.
As a result of the work done, we have studied the parameters of asteroids approaching the Earth. To model these processes, we have developed mathematical models of body motion. We have developed a software package (Delphi VII) to study and visualize the asteroid motion before the collision and after changing the trajectory by the kinetic interceptor. With the help of the software we have obtained visualization of the processes of deflection of a dangerous asteroid using the method.

Analyzing the data obtained, we can conclude that the calculations with the specified characteristics of the kinetic interceptor to divert the threat from Apophis's orbit is less than 1 years.
4. References

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