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ORBIT PATH FILTER FOR DETECTION OF DANGEROUS SATELLITE-SATELLITE AND SATELLITE-SPACE DEBRIS CLOSE APPROACHES

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Abstract: *The constantly growing space debris population poses a significant increasing of collision risk with operational satellites. The development of approaches and algorithms for evaluation of the collision risk for satellites and other orbiting objects is of fundamental importance in space situational awareness programs.*

The minimum orbital intersection distance is used for the fast identification of potentially hazardous near Earth objects. Orbit Path Filter for Detection Satellite-Satellite Close Approaches based on orbital line of intersection is proposed. One of the conditions for collision is two orbiting objects to be located on the line of intersection between the Kepler's orbit planes. The transformation of intersection line toward orbital plane of the first object and later on toward orbital plane of the second one allows easily calculation of its intersection points with Keplers' ellipses. The comparison between calculated coordinates for points of couple objects transformed to geo-equatorial coordinate system determines close hazardous orbits' approaches.

The proposed approach is based on exact solutions of algebraic systems for determination of points of passing of satellites through orbits' intersection line.

ГЕОМЕТРИЧЕН ФИЛТЪР ЗА ОТКРИВАНЕ НА ОПАСНИ СБЛИЖАВАНИЯ МЕЖДУ СПЪТНИЦИ СЪС СПЪТНИЦИ И СПЪТНИЦИ С ОРБИТАЛНИ ОТЛОМКИ

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Резюме*: Постоянното увеличаване на космическия боклук води до увеличаване на риска от сблъскване със спътници, чиито експлоатационен период не е изтекъл. Разработката на подходи и алгоритми за оценка на риска от стълкновение между спътници и други обекти е от изключителна важност за неговото намаляване и избягване. Минималното разстояние между орбитите върху тяхната пресечница се използва за бърза идентификация на потенциално опасни обекти на околоземна орбита. Предложен е „Orbit Path Filter" за установяване на сближавания между спътници, основан на пресечницата между орбиталните равнини. Едно от условията за стълкновение между два обекта е да се намират на пресечницата на двете Кеплерови равнини. Трансформацията на пресечницата към орбитална координатна система, свързана с орбитата на първия спътник, и след това съответно за втория, позволява лесно изчисляване на пресечните им точки с Кеплеровите им елипси. Сравняването на изчислените координати на точките за двойка обекти, трансформирани към гео-екваториална координатна система, определя възможни опасни орбитални сближавания.*

Предложеният подход се основава на точни решения на алгебричните системи уравнения за определяне на точките на преминаване на спътниците през пресечната линия между орбитите им.

Introduction

The space activity of mankind crowds the space around the Earth with different debris from rockets and rockets engines which move without any control by its orbits with possibilities to approach to operating satellites. The number of these debris steadily increase and raise the risk of direct collisions, which can destroy or damage some instruments of the satellites or cancel part or entire missions. This lead to establishment of new scientific discipline, connected with risk assessment and development of total control on behavior of orbiting particles and strategies for risk mitigation and escaping damaging of operation satellites.

The exact determination of the conjunction between objects on Earth orbit is possible on the base of numerical integration of their motion equations. One simplified problem is connected with finding possible approaches between important operative satellites with aim to escape their direct collisions. More general problems are connected with prediction of possible approaches between operative satellites and space debris, or between big debris. The collisions between big debris will increase the number of debris particles. Estimation of the number of objects with size bigger than 10 cm is about 29,000 and bigger than 1cm is about 740,000 [1]. The solution of these problems can be obtained after solving huge number of equations of motion, which is difficult from computing point of view. Different simulation experiments are performed [2, 3, 4, 5] with number of objects between $8x10^3$ and $30x10^3$.

Hoots developed and proposed three types of analytical filters [6]. With them the possibility for close approach between two orbiting bodies could be evaluated relatively easy. Precise calculations are performed only for couple of objects with threat for collision under some critical threshold D^*.

An analytical method for situational analysis based on transformation of situation condition toward Kepler's plane was proposed [7].

This method solves some classes of situation problems by representing situational conditions using respective geometrics objects - strait lines, conical, cylindrical or parabolic surfaces.

In this article threat conjunctions between two orbiting objects lie on interception line of their orbital no-coplanar planes. Very simple method based on transformation of interception line toward orbital planes is proposed.

Determination of intersection between two Kepler's plains in geo-equatorial coordinate system

The 6-tuple $<a,e,i,\Omega,\omega,\tau_0>$ fully determines Kepler's orbits [8]. The different symbols denote respectively: a - major semi-axis, e - eccentricity, i - inclination, Ω - argument of ascending node, ω - argument of perigee and τ_0 - moment of passing through perigee. We may say that $<i,\Omega>$ - determine the orientation of Kepler's plane (fig. 1), $<\omega>$ - the orientation of Kepler's orbit in orbital plane, $<\tau_0>$ - the object position on the orbit and $<a,e>$ - the shape of the orbital ellipse.

The Kepler's plane is determined by mixed product in Geo-equatorial coordinate system (GEcs):

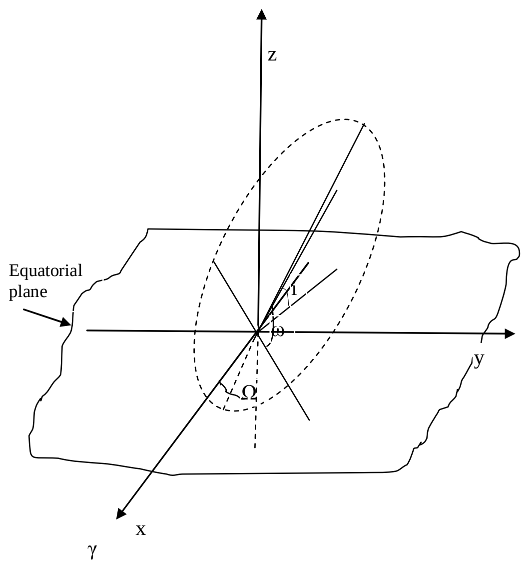

Figure 1. Kepler's orbit in orbital coordinate system

1. $\vec{x}\,.\,\vec{b}\times\vec{c}=0$,

where the unit vector $\vec{b}$ is collinear to intersection between equatorial plane and Kepler's plane and is pointed to point of autumnal equinox - γ. The unit vector $\vec{c}$ is collinear to the large axis of Kepler's ellipse and is directed to his perigee. These two vectors can be written in terms of <i,Ω> as:

2. $$\begin{array}{lll} b_x = \cos\Omega & b_y = \sin\Omega & b_z = 0 \\ c_x = \cos(\Omega+.5\pi).\cos i & c_y = \sin(\Omega+.5\pi).\cos i & c_z = \sin i \end{array}$$

The unit vector $\vec{n}$ normal to Kepler's plane could be presented as:

3. $\vec{n}=\vec{b}\times\vec{c}$

The unit vector $\vec{\tau}$ collinear to intersection line between the two orbital planes of two satellites (fig. 2) is:

4. $\vec{\tau}=\vec{n}_1\times\vec{n}_2$

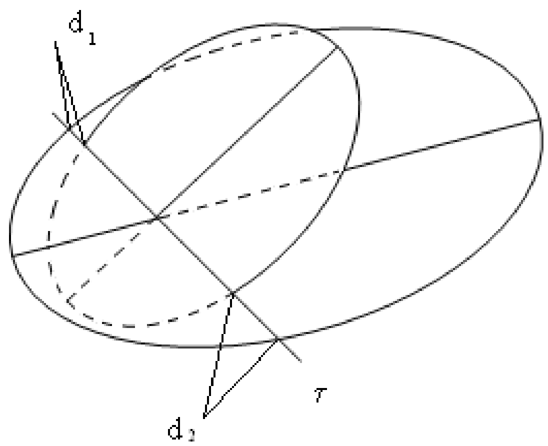

Figure 2. Intersection line between two Kepler's orbits-a place for collisions

Determination the closest approach distance between two elliptic orbits along the intersection line of Keplers' planes

From historical point of view, the first investigations of conjunction problems are related to close approaches of asteroids and comets to planets [9, 10]. Some recent authors continue the development of such problematic [11, 12]. Different authors determine the closest approach between two orbits and in general case, this orbital conjunction couldn't lie on intersection line [3, 4, 13]. We define dangerous conjunctions on the presumption that collision between two orbiting objects is possible only when they lie on intersection line. Each of the satellites must be located in orbital plane of the other one.

Let transform intersection line τ from GEcs toward orbital coordinate system (Ocs) (fig. 3):

5. $\tau' = \alpha\tau$,

where α is transformation matrix [8]. We could consider the system of two equations:

6. $$\left\|\begin{array}{l} \dfrac{(\xi + c)^2}{a^2} + \dfrac{\eta^2}{a^2.(1-e^2)} = 1 \\ \eta = k.\xi \end{array}\right.$$

The first one is equation of Kepler's ellipse, which focus is located in origin of Ocs. Thus this equation is not canonical. The second equation is for straight line passing through origin of orbital coordinate system. The solution of system (6) is easily produced by consecutively substitution of variables η and ξ in the first equation and elementary transformations to quadratic equation. The two roots of (6) correspond to two points (η_1,ξ_1) and (η_2,ξ_2), where τ' intersects the Kepler's ellipse.

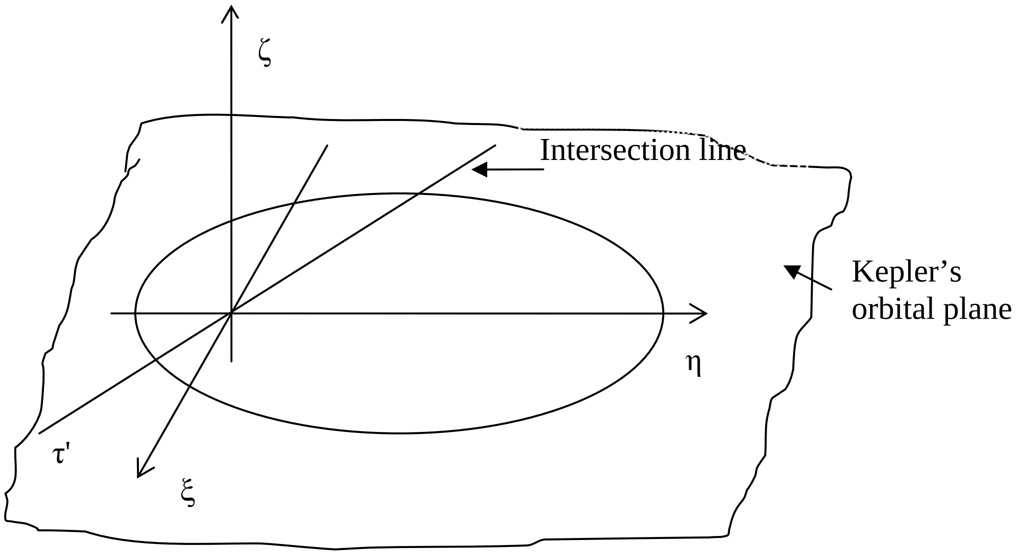

Figure 3. Kepler's orbit and intersection line in orbital coordinate system

The application of this procedure for a couple of orbital planes produces two couples of points - $((\eta_1,\xi_1)_I, (\eta_2,\xi_2)_I)$ and $((\eta_1,\xi_1)_{II}, (\eta_2,\xi_2)_{II})$ for every object. The transformation of the two points $(\eta_1,\xi_1)_I$ and $(\eta_2,\xi_2)_I$ from first and the two points $(\eta_1,\xi_1)_{II}$ and $(\eta_2,\xi_2)_{II}$ from the second orbital plane toward GEcs allows to calculate the two distances on intersection line - d_1 and d_2 (Fig. 2).

Evolution of Kepler's ellipse in the time

Orbital elements $<a,e,i,\Omega,\omega,\tau_0>$ are changing under influences of different perturbations [8,14]. We may write down for every one of them:

$$
\begin{aligned}
a_{0+t} &= a_0 + \Delta a_T = a_0 + \dot{a}\Delta t \\
e_{0+t} &= e_0 + \Delta e_T = e_0 + \dot{e}\Delta t \\
i_{0+t} &= i_0 + \Delta i_T = i_0 + \dot{i}\Delta t \\
\Omega_{0+t} &= \Omega_0 + \Delta\Omega_T = \Omega_0 + \dot{\Omega}\Delta t \\
\omega_{0+t} &= \omega_0 + \Delta\omega_T = \omega_0 + \dot{\omega}\Delta t \\
\tau^0_{0+t} &= \tau^0_0 + \Delta\tau^0 = \tau^0_0 + \dot{\tau}^0\Delta t
\end{aligned}
$$

The secular changes in the orbital elements lead to changes of ellipses and orbital planes of every couple orbiting objects. The intersection between the two orbital planes of the couple of objects is changed too. Finally we have to apply the above described procedure to determine the distance on intersection line after change of orbital elements for every object.

Explained approach for determination of the distance between two Kepler's ellipses on their orbital planes intersections is very similar to another one, solved by transformation of situation condition toward Kepler's plane [7].

Conclusion

A multitude of subroutines was developed for solving broad classes of situation problems. Every class situation problems is based on different geometric objects for representation of the situation condition. The transformation of these geometrics objects toward orbital plane results in different power curves. The algorithm to solve the presented problem could be organized on the base of the simplest one – passing of two satellites over the same place of Earths' surface.

Presented approach is based on non-iterative methods for solving of applied equations. The transformation from geo-equatorial coordinate system toward orbital one is significant from calculation point of view. It contains only 29 sin and cos functions and 20 float point operations.

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