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WITH VELOCITY-GAIN GUIDANCE

by

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REALIZATION OF TARGET SATELLITE INTERCEPTION
WITH VELOCITY-GAIN GUIDANCE

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ABSTRACT:

This paper is about the study of realization of the target satellite interception method with velocity gain guidance. The characteristics are the following: based on the given conditions of the interceptor's initial motion parameters and the target's trajectory parameters, firstly the predictive point of impact intercepting the target under the influence of J2 item of the earth oblatness is determined, then the interceptor's velocity required during the collision time using Lambert method is decided, at last, the target interception with velocity gain guidance method is realized. A transform condition with higher precision to the terminal guidance by using this method is guaranteed.

Key words interception, trajectory, velocity gain guidance

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The article attempts to use the velocity-gain guidance method in target satellite interception by an interceptor. Several problems are emphasized in the discussion of the earth oblateness J_2 affecting the determination of the predicted interception point, and the realization of the guidance method.

In the launch inertial coordinate system determined by the firing angle A_0 and the geographic latitude B_0, assume that point D in space for the interceptor at time t_1 has the following motion parameters:

$$\vec{\rho}_D(t_1) = [x_D(t_1) \quad y_D(t_1) \quad z_D(t_1)]^T \tag{1}$$
$$\vec{v}_D(t_1) = [v_{Dx}(t_1) \quad v_{Dy}(t_1) \quad v_{Dz}(t_1)]^T \tag{2}$$

It is required to locate the space position point M at which the target will be intercepted at t_1 + T calculated for an orbit after time T:

$$\vec{\rho}_M(t_1 + T) = [x_M(t_1 + T) \quad y_M(t_1 + T) \quad z_M(t_1 + T)]^T \tag{3}$$

correspondingly, at times t_1 and t_1 + T, the geocentric points of the interceptor position at times t_1 and t_1 + T are, respectively

$$\vec{r}_D(t_1) = [x_D(t_1) + R_{0x} \quad y_D(t_1) + R_{0y} \quad z_D(t_1) + R_{0z}]^T \tag{4}$$
$$\vec{r}_M(t_1 + T) = [x_M(t_l + T) + R_{0x} \quad y_M(t_1 + T) + R_{oy} \quad z_M(t_1 + T) + R_{0z}]^T \tag{5}$$

In the equations, $\vec{R}_0 = [R_{0x}\, R_{0y}\, R_{0z}]^T$ is the geocentric-radius vector of the firing point.

I. Determination of the Predicted Interception Point

According to elliptic theory, an elliptical trajectory can be determined for two points in space constrained in the given flight time. In addition, the required velocity at the beginning point can be determined. Actually, the interceptor does not fly in an inverse-square law gravity field law. After the given flight time, the interceptor is unable to collide with the target, thus affecting the transformation condition for transforation at the terminal-guidance phase. To reduce the error due to the earth's oblateness, let us adopt the method of the predicted interception point. After revising with respect to oblateness, the interception point is called the predicted interception point. Considering that in the gravity field of the J_2 term, if the interceptor has the required velocity determined by the predicted interception point, then after flying the interceptor just arrives at the required interception point.

First, the effect of J_2 is not considered. According to $\vec{r}_D$、$\vec{r}_M$ and the flight time T to determine an elliptical trajectory and the instantaneous required velocity $\vec{v}_R$: (including velocity v_R, velocity dip angle θ_R, and azimuth angle A_R at the elliptic trajectory plane). Moreover, the corresponding geocentric latitudes $\vec{r}_D$ and $\vec{r}_M$ correspond to points ϕ_D and ϕ_M, as well as the radial difference λ_{DM} and geocentric angle β_M. Then, by using the perturbation theory [1] employed in standard trajectories to determine the effect of the J_2 term on the interception point, and the effect on flight time. Then we can derive the equal-altitude firing range angle $\vec{r}_M$, the equal-altitude lateral-deviation angle ζ_M, and the time deviation $\Delta_r\beta_M$ arrived at the ground surface, with respect to the distance between the interception point and the ground track point that the interceptor arrives as determined by the interception point $\Delta_r T$. Convert $\Delta_r\beta_M$ and ζ_M to the linear deviation quantity of the $\vec{r}_M$ point of the right-handed inertial coordinate system of the X-axis, for the firing direction at the subsatellite point with respect to point D:

$$\begin{bmatrix}\Delta x_M\\ \Delta y_M\\ \Delta z_M\end{bmatrix}=\begin{bmatrix}r_M\cos\beta_M\Delta_r\beta_M\\ -r_M\sin\beta_M\Delta_r\beta_M\\ r_M\zeta_M\end{bmatrix} \qquad (6)$$

At the subsatellite point for D, the various deviation quantities in the north-sky-east coordinate system

$$\begin{bmatrix} \Delta x_\varphi \\ \Delta y_r \\ \Delta z_\lambda \end{bmatrix} = \begin{bmatrix} \cos A_R & 0 & -\sin A_R \\ 0 & 1 & 0 \\ \sin A_R & 0 & \cos A_R \end{bmatrix} \begin{bmatrix} \Delta x_M \\ \Delta y_M \\ \Delta z_M \end{bmatrix} \tag{7}$$

Convert into deviation quantities in the launch inertial coordinate system

$$\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} = \begin{bmatrix} f_{11}/\cos\varphi_D & r_{Dx}^0 & f_{31}/\cos\varphi_D \\ f_{12}/\cos\varphi_D & r_{Dy}^0 & f_{32}/\cos\varphi_D \\ f_{13}/\cos\varphi_D & r_{Dz}^0 & f_{33}/\cos\varphi_D \end{bmatrix} \begin{bmatrix} \Delta x_\varphi \\ \Delta y_r \\ \Delta z_\lambda \end{bmatrix} \tag{8}$$

In the equations,

$$\begin{cases} f_{11} = \Omega_x^0 - \sin\varphi_D r_{Dx}^0 \\ f_{12} = \Omega_y^0 - \sin\varphi_D r_{Dy}^0 \\ f_{13} = \Omega_z^0 - \sin\varphi_D r_{Dz}^0 \\ f_{31} = \Omega_y^0 r_{Dz}^0 - \Omega_z^0 r_{Dy}^0 \\ f_{32} = \Omega_z^0 r_{Dx}^0 - \Omega_x^0 r_{Dz}^0 \\ f_{33} = \Omega_x^0 r_{Dy}^0 - \Omega_y^0 r_{Dx}^0 \end{cases} \tag{9}$$

$$\begin{bmatrix} r_{Dx}^0 \\ r_{Dy}^0 \\ r_{Dz}^0 \end{bmatrix} = \frac{1}{r_D} \begin{bmatrix} R_{0x} + x_D \\ R_{0y} + y_D \\ R_{0z} + z_D \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} \Omega_x^0 \\ \Omega_y^0 \\ \Omega_z^0 \end{bmatrix} = \begin{bmatrix} \cos B_0 \cos A_0 \\ \sin B_0 \\ -\cos B_0 \sin A_0 \end{bmatrix} \tag{11}$$

Finally, reduce the deviation quantity due to oblateness from the interception point $\vec{r}_M$, then the position parameter $\vec{r}_M^{*}$ of the predicted interception point is

$$\vec{r}_M^{*} = [\vec{r}_{Mx}^{*} \quad \vec{r}_{My}^{*} \quad \vec{r}_{Mz}^{*}]^T = [R_{0x} + x_M^{*} \quad R_{0y} + y_M^{*} \quad R_{0z} + z_M^{*}]^T \tag{12}$$

In the equation,

$$\begin{bmatrix} x_M^{\bullet} \\ y_M^{\bullet} \\ z_M^{\bullet} \end{bmatrix} = \begin{bmatrix} x_M - \Delta x \\ y_M - \Delta y \\ z_M - \Delta z \end{bmatrix} \tag{13}$$

There is a time deviation $\Delta_r T$ as the interceptor flies to the interception point in the inverse-square law gravity field. Therefore, a revision should also be made. In other words, it is required that the interceptor fly to rm in the inverse-square law gravity field within the time $T^*=T-\Delta_r T$.

II. Determination of Required Velocity for Fixed Interception Time

Now the problem, based on the real-time position $\vec{r}_M^{\bullet}$ and the position $\vec{r}_D$ of the predicted interception point of the interceptor, is to determine the required velocity $\vec{v}_R^{\bullet}$ for the interceptor to arrive at the predicted interception point in an inverse-square gravity field within the time period T^*. This point can be solved by using the Lambert method [3]. Moreover, from the geocentric vector-radii $\vec{r}_D$ and $\vec{r}_M^{\bullet}$, we can determine the sine and cosine values of the great-arc azimuth angle AR of the elliptical orbital plane defined by $\vec{r}_D$ and $\vec{r}_M^{\bullet}$, from the longitude difference $\lambda_{DM}^{\bullet}$ between the two points of geocentric latitudes ϕ_D and ϕM.

$$\begin{cases} \sin A_R^{\bullet} = \cos\varphi_M^{\bullet} \sin\lambda_{DM}^{\bullet}/\sin\beta_M^{\bullet} \\ \cos A_R^{\bullet} = (\cos\varphi_M^{\bullet} - \cos\beta_M^{\bullet}\sin\varphi_D)/(\sin\beta_M^{\bullet}\cos\varphi_D) \\ \beta_M^{\bullet} = \arccos[\vec{r}_D \cdot \vec{r}_M^{\bullet}/(r_D r_M^{\bullet})] \end{cases} \tag{14}$$

Thus, it is required that the projection of velocity vR in the launch inertial coordinate system be given as

$$\begin{bmatrix} v_{Rx}^{\bullet} \\ v_{Ry}^{\bullet} \\ v_{Rz}^{\bullet} \end{bmatrix} = v_R^{\bullet} \begin{bmatrix} f_{11}/\cos\varphi_D & r_{Dx}^0 & f_{31}/\cos\varphi_D \\ f_{12}/\cos\varphi_D & r_{Dy}^0 & f_{32}/\cos\varphi_D \\ f_{13}/\cos\varphi_D & r_{Dz}^0 & f_{33}/\cos\varphi_D \end{bmatrix} \begin{bmatrix} \cos\Theta_R^{\bullet}\cos A_R^{\bullet} \\ \sin\Theta_R^{\bullet} \\ \cos\Theta_R^{\bullet}\sin A_R^{\bullet} \end{bmatrix} \tag{15}$$

In the equation, Θ_R^* is the dip angle of the required velocity $\vec{v}_R^*$.

III. Realization of Velocity-Gain Guidance Method

Generally, we call the difference between the instantaneous required velocity $\vec{v}_R^*$ and its real-time velocity $\vec{v}_D$ of the interceptor as follows:

$$\vec{v}_g = \vec{v}_R^* - \vec{v}_D \tag{16}$$

In the equation, $\vec{v}_g$ is the velocity gain.

In principle, align the booster-acceleration direction and the gain-velocity direction of the interceptor so that after time tau of engine burn, the interceptor measurement apparatus provides velocity and position parameters at a new time instant, and repeat the foregoing steps to continue the guidance. We should point out that if the time is T as specified for the interceptor from the beginning guidance point to the interception point, then n iterations will subtract n times tau from T.

Besides the foregoing fundamental concept, the following problems can be considered in engineering practice.

3.1. Estimation of required velocity, and improvement of velocity-gain at engine shutoff point

To save fuel and to allow the interceptor have a more stable attitude near the engine shutoff point, we consider using the required velocity $\vec{v}_{R,k}^*$ at the estimated engine shutoff point to replace the instantaneous required velocity $\vec{v}_R^*$.

Series expansion at the time instant t_i with respect to the velocity-gain $\vec{v}_g$ and the required velocity $\vec{v}_R^*$, we select the following, in approximate terms:

$$\vec{v}_{g,k} = \vec{v}_g(t_k) = \vec{v}_g(t_i) + \dot{\vec{v}}_g(t_i)(t_k - t_i) \tag{17}$$

$$\vec{v}^{*}_{R,k} = \vec{v}^{*}_R(t_k) = \vec{v}^{*}_R(t_i) + \dot{\vec{v}}^{*}_R(t_i)(t_k - t_i) \tag{18}$$

In the equation,

$$\dot{\vec{v}}_g(t_i) \approx [\vec{v}_g(t_i) - \vec{v}_g(t_{i-1})]/\tau$$
$$\dot{\vec{v}}^{*}_R(t_i) \approx [\vec{v}^{*}_R(t_i) - \vec{v}^{*}_R(t_{i-1})]/\tau$$
$$\tau = t_i - t_{i-1}$$

we also know when t_i--->t_k, vg,k--->0, therefore from Eq. (17), we know

$$t_k\text{-}t_i = -[\vec{v}_g(t_i) \cdot \dot{\vec{v}}_g(t_i)]/|\dot{\vec{v}}_g(t_i)|^2 \tag{19}$$

$$\vec{v}^{*}_{R,k} = \vec{v}^{*}_R(t_i) - \frac{1}{\tau}[\vec{v}^{*}_R(t_i) - \vec{v}^{*}_R(t_{i-1})][\vec{v}_g(t_i) \cdot \dot{\vec{v}}_g(t_i)]/|\dot{\vec{v}}_g(t_i)|^2 \tag{20}$$

Eq. (20) is the estimated vector-equation for the velocity required at the engine shutoff point.

Consideration is given to the effect of gravity in the time interval between t_i and t_k, and the gravity acceleration within this time period is considered as the $\vec{g}_D$, then the improved velocity-gain of the interceptor can be expressed as:

$$\begin{aligned}\vec{v}'_g &= \vec{v}^{*}_{R,k} - \vec{v}_D(t_i) - \vec{g}_D(t_i)(t_k - t_i)\\ &= \vec{v}^{*}_R(t_i) - \vec{v}_D(t_i) - \left[\frac{\vec{v}^{*}_R(t_i) - \vec{v}^{*}_R(t_{i-1})}{\tau} - \vec{g}_D(t_i)\right][\vec{v}_g(t_i) \cdot \dot{\vec{v}}_g(t_i)]/|\dot{\vec{v}}_g(t_i)|^2\end{aligned} \tag{21}$$

3.2. Determination of interceptor attitude

Assume that the booster apparatus of the interceptor is composed of four constant-value small-booster engines vertical to the interceptor main axis o_1x_1, as installed on the o_1y_1 and the o_1x_1 axis cruciformly surrounding the mass center. When applying thrust-vectoring fixation in the $\vec{v}_g'$ direction, the attitude-control scheme of the interceptor is various. If we base our calculations on the principle of minimum change in attitude angle, to select the single o_1y_1 and the o_1z_1 axis direction of the engine, in the $\vec{v}_g'$ vector direction, to provide thrust, or to allow the combined thrust of the o_1y_1 and o_1z_1 axes with $\vec{v}_g'$ to be coplanar to simultaneously start two engines for guidance control. A simpler scheme is to use the positive thrust from the o_1y_1 axis to align the direction with the $\vec{v}_g'$ direction, for guidance. If it is assumed that the interceptor coordinate system at the beginning guidance point is coincident with the platform coordinate system, then the attitude control angle of the interceptor is

$$\begin{cases} \varphi = \mathrm{arctg}(v'_{gy}/v'_{gx}) - \mathrm{sign}(v'_{gx} \cdot \frac{\pi}{2}), \ -\pi \leqslant \varphi \leqslant \pi \\ \psi \equiv 0 \\ \gamma = \mathrm{arctg}(v'_{gz}/\sqrt{v'_{gx} + v'_{gy}}), \ -\frac{\pi}{2} \leqslant \gamma \leqslant \frac{\pi}{2} \end{cases} \tag{22}$$

3.3. Control of engine shutoff point

When conducting computations for the engine shutoff condition, the interceptor-borne computer has a time lag error. Assume that the computation step length is τ, then the engine shutoff time error can be between tau and 2τ. To reduce the control error at the engine shutoff point, the two following measures can be considered to upgrade guidance accuracy.

(1) A linear prediction is conducted on the engine shutoff

time in order to determine the time of simplified computation using the guidance equation.

$\vec{v}_{r}'$ at time t near the engine shutoff point can be considered as a linear function of time. Then, Eq. (19) can be used to determine the time interval (t_k-t) from t to t_0 to t_k, the time τ of engine shutoff point. Allowance is given to the fact that before the use of the small-step length, the time length error of the interceptor-borne computations is τ', the original computation step length. Therefore, selecting the time for simplified computations of the guidance equation is the first to satisfy the time t

$$t_k - t \leqslant 2\tau + 2\tau' \tag{23}$$

(2) Simplified equation of guidance equation when calculating small-step length near engine shutoff point

After determining the time t satisfying Eq. (23), actually the interceptor-borne engine has operated for a step τ. By marking t_T=t+τ, thus beginning at t_T, the small-step length computation commences. Generally speaking, only when the computer run time does not exceed τ+2τ, which is a very short time, therefore, the general guidance equation can be simplified. If the time parameter T is used as the basis, the real-time velocity is $\vec{v}_D'$, the required velocity is $\vec{v}_R^*$, then the extrapolated velocity gain $\vec{v}_g'$ of the interceptor can be obtained.

$$\vec{v}_D(t_T + n\tau') = \vec{v}_D(t) + \frac{1}{\tau}[\vec{v}_D(t) - \vec{v}(t-\tau)](\tau + n\tau') \tag{24}$$

$$\vec{v}_R^*(t_T + n\tau') = \vec{v}_R^*(t) + \frac{1}{\tau}[\vec{v}_R^*(t) - \vec{v}_R^*(t-\tau)](\tau + n\tau') \tag{25}$$

$$\vec{v}_g(t_T + n\tau') = \vec{v}_R^*(t_T + n\tau') - \vec{v}_D(t_T + n\tau') \tag{26}$$

In the equations, n=1,2,... is the number of iterative computations after using the small-step length. Thus, Eq. (19) can be used to calculate the value $(t_k - t_T - n\tau')$. Take note that guidance of the interceptor is not necessary within a very short time near the engine shutoff point. Now, the attitude is the attitude of the final large-step length. The reason is that the tiny variation in the interceptor attitude within a very short time does not have much effect on the motion of the mass center. Besides, the slowly-varying g_D is considered as a constant. By considering the accuracy of the linear prediction and the feasibility of prediction when calculating the time delay and the engine shutoff time, the first-appearing

$$t_k - t_T - n\tau' \leqslant 2\tau' \tag{27}$$

is considered as the determination condition of issuing the linear prediction. Then, when the above equation is established, the computation formula for the engine shutoff time is

$$t_k = t_T + n\tau' - \left.\frac{\vec{v}_g \cdot \dot{\vec{v}}_g}{|\dot{\vec{v}}_g|^2}\right|_{t_T + n\tau'} \tag{28}$$

IV. Numerical Simulation Results and Discussion

4.1. Simulation results

Assume that the constant thrust acceleration generated by each engine is $0.5g_0$, when the foregoing scheme is adopted, the simulation results of a typical interception trajectory is as follows: the guidance operating time is 29.196s, at the 150km distance between the interceptor and the target satellite, when the terminal guidance phase begins, the line-of-sight rotating rate for the relative motion of the two is $3.096 \times 10^{-6}/s$; this entirely satisfies the initial conditions for terminal guidance.

4.2. Analysis and discussion

(1) By using the predicted interception point after modification with the oblateness J_2 term, the velocity-gain guidance is conducted, along with measures of simplified computation at the predicted engine shutoff time and near the engine shutoff point, along with the use of small-step length computation, the error is very small when use is made of the method of guidance based on simulation results. When there is no external interference, in the guidance process the engine is started up only once. It is apparently that the use of the velocity-gain guidance method to accomplish the guidance task is feasible.

(2) In engineering practice, if problems of computer memory and operating speed are encountered when using this guidance method, consideration is given not to use the method of the post-modified predicted intersection point, but to use the required velocity vR for guidance in the inverse-square law gravity field obtained from the given interception point. In other words, multiple engine firings are required to continuously update the error in guidance when not considering the effect of oblateness, to improve the guidance accuracy.

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