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Terminal Guidance Technology for On-orbit Refuelling Based on Model Predictive Control

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Abstract: On-orbit refuelling refers to the on-orbit operation of using a service spacecraft to supply propellant to the target spacecraft in space orbit, refuelling the target spacecraft to re-enter the working state and prolong its working time. Rail refuelling technology has a wide range of application prospects. The terminal guidance technology solves the maneuver transfer from short range to rendezvous and docking process and is one of the key technologies for on-orbit supplementation. Taking into account the nonlinearity, time-varying and strong coupling of the spacecraft maneuvering process, this paper proposes a fuel on-orbit end-stage guidance technology based on model predictive control, so that the control process does not depend on accurate system models to achieve high quality control.

1. Introduction

With the rapid development of aerospace technology, the number of spacecraft in orbit has gradually increased, resulting in increasingly tight space resources. At the same time, technological progress has greatly reduced the probability of a spacecraft carrying equipment malfunctioning, and fuel limitations have become the main factor restricting the long-term orbit of the spacecraft. Therefore, various aerospace powers have put forward the idea of "spacecraft refuelling in orbit" to enhance the maneuverability and working life of orbiting spacecraft. When refuelling in orbit, the maneuvering process of the service spacecraft can generally be divided into four stages. First, Through long-range guidance to the target spacecraft within a range of 15-100km, and then through short-range guidance to narrow the distance to 0.5-1km, and then through the final approach to within 100m, and finally complete docking and docking. The terminal guidance technology proposed in this paper mainly solves the maneuvering problem within the last 1km range.

2. Problem description

During the orbital refuelling process, it is generally believed that the target spacecraft has no maneuverability, and the service spacecraft needs to use thrusters to maintain visual contact and docking with the target spacecraft. In order to increase the service life of the spacecraft and refuel as many target spacecraft as possible within a unit time, in most cases, the problem of on-orbit refuelling should minimize the combination of fuel consumption and maneuver flight time. In order to ensure the safety of the entire filling process, the following requirements should be met:

- No collision between spacecraft.
- The target spacecraft must always be kept within the detection angle of the service spacecraft vision or other detection equipment.
- During the final docking, the ignition amount of the thruster towards the target spacecraft must be minimized to reduce the plume impact.

In the process of terminal guidance, the fuel consumption of the service spacecraft is negligible relative to its own weight. Therefore, within the scope of the problem studied in this paper, the quality of the service spacecraft is considered to be a fixed value during the entire docking process.

The relative movement of the two spacecraft is centered on the target spacecraft, moving vertically and horizontally. The Z axis points to the center of the earth, the Y axis is aligned with the negative orbital normal, and the X axis forms a right-handed coordinate system with the Y and Z axes in the orbital plane. The relative position vector is represented by $\delta r = [x, y, z]^T$, Where x, y, and z are the along-track, cross-track and radial components, respectively. Here, we take a circular orbit as an example to illustrate that after ignoring the small interference, the HCW (Hill-Clohessy-Wiltshire) equation of the problem can be established.

$$\begin{cases} \ddot{x} = 2\omega\dot{z} + \frac{u_1}{m} \\ \ddot{y} = -\omega^2 y + \frac{u_2}{m} \\ \ddot{z} = 3\omega^2 z - 2\omega z + \frac{u_3}{m} \end{cases} \tag{1}$$

Among them, u_1,u_2 and u_3 are the control power of the service spacecraft expressed in the local horizontal coordinate system (LVLH), m is the mass of the service spacecraft, and ω is the LVLH rotation rate.

The location of the docking port can be described as $\delta r_d = [x_d, 0,0]^T, x_d = const.$

Since the radial thrust is not available, $u_3 = 0$ in the control vector, the control vector can be further simplified as: $u = [u_1, u_2]^T$.

The tracking error is represented by the following publicity:

$$x = [x_1, \ldots, x_6] = [(\delta r - \delta r_d)^T, (\delta\dot{r} - \delta\dot{r}_d)^T]^T \tag{2}$$

Using the linearized HCW equation, the tracking error dynamics is represented by the state space model as:

$$\dot{\boldsymbol{x}} = \boldsymbol{A_c x} + \boldsymbol{B_c u} \tag{3}$$

Among them,

$$\boldsymbol{A_c} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 2\omega \\ 0 & -\omega^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3\omega^2 & -2\omega & 0 & 0 \end{bmatrix}, \boldsymbol{B_c} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{m} \\ \frac{1}{m} & 0 \\ 0 & 0 \end{bmatrix} \tag{4}$$

Assuming that the system is completely observable, the system adopts the zero-order hold sampling period T_s to discretize, and the discrete state space model can be obtained as:

$$\boldsymbol{x}(k+1) = \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}\boldsymbol{u}(k) \tag{5}$$

$$\boldsymbol{A} = e^{\boldsymbol{A_c}T_s}, \boldsymbol{B} = \left(\int_0^{T_s} e^{\boldsymbol{A_c}\tau} d\tau\right) \boldsymbol{B_c} \tag{6}$$

3. Model predictive control

Model predictive control takes the spacecraft docking model obtained from the HCW equation as the predictive model, and regards the state response of the controlled object and the weighted quadratic form of the control input as performance indicators, and at the same time obtains constraint conditions based on various performance indicators. Through online rolling optimization and self-correction feedback, the dynamic influence of the uncertain and time-varying factors of the controlled object can be effectively solved, and the goal of predictive control can be realized.

Considering the constraints of the detection sensor's field of view, a high-precision nonlinear simulation model is established. The state vector of the model includes the position and velocity vectors of the target spacecraft (r_L, v_L) and the service spacecraft (r_F, v_F). The dynamic equation in the earth-centered inertial coordinate system is expressed as:

$$\dot{\boldsymbol{r}}_L = \boldsymbol{v}_L \tag{7}$$

$$\dot{\boldsymbol{v}}_L = -\frac{\mu}{r_L^3}\boldsymbol{r}_L + \boldsymbol{a}_L \tag{8}$$

$$\dot{\boldsymbol{r}}_F = \boldsymbol{v}_F \tag{9}$$

$$\dot{\boldsymbol{v}}_F = -\frac{\mu}{r_L^3}\boldsymbol{r}_F + \boldsymbol{a}_F, \boldsymbol{v}_F^+ = \boldsymbol{v}_F^- + \Delta\boldsymbol{v}_F \tag{10}$$

Among them, μ is the earth's gravitational constant; the perturbation accelerations $\mathbf{a}_L$ and $\mathbf{a}_F$ are calculated based on the main orbital perturbations acting on the spacecraft at low altitude. Then the true relative position and velocity are expressed in the LVLH model as:

$$\delta\boldsymbol{r} = \boldsymbol{R}_L^I(\boldsymbol{r}_F - \boldsymbol{r}_L) \tag{11}$$

$$\delta\dot{\boldsymbol{r}} = \boldsymbol{R}_L^I(\boldsymbol{v}_F - \boldsymbol{v}_L) - [\omega\ \times]\boldsymbol{R}_L^I(\boldsymbol{r}_F - \boldsymbol{r}_L) \tag{12}$$

LVLH rotation angular velocity can be given as: $\omega = -\sqrt{\frac{\mu}{\|\boldsymbol{r}_L\|_2^3}}$

Given the control model, the state quantity of the k+2th term is:

$$\begin{aligned}\boldsymbol{x}(k+2) &= \boldsymbol{Ax}(k+1) + \boldsymbol{Bu}(k+1)\\ &= \boldsymbol{A}(x(k) + \boldsymbol{Bu}(k)) + \boldsymbol{B}(\boldsymbol{u}(k) + \Delta\boldsymbol{u}(k))\\ &= \boldsymbol{A}^2\boldsymbol{x}(k) + (\boldsymbol{AB} + \boldsymbol{B})\boldsymbol{u}(k) + \boldsymbol{B}\Delta\boldsymbol{u}(k)\end{aligned} \tag{13}$$

Assuming that p terms are predicted, in actual control, the control quantity of the next p cycles is unknown. First, assuming that the control quantity of the next p cycles remains unchanged, all of which are u(k-1), then the control object can be obtained The a priori predicted value is:

$$\begin{cases}\boldsymbol{x}_0(k+1|k) = \boldsymbol{Ax}(k) + \boldsymbol{Bu}(k-1)\\ \boldsymbol{x}_0(k+2|k) = \boldsymbol{Ax}_0(k+1|k) + \boldsymbol{Bu}(k-1)\\ \vdots\\ \boldsymbol{x}_0(k+P|k) = \boldsymbol{Ax}_0(k+P-1|k) + \boldsymbol{Bu}(k-1)\end{cases} \tag{14}$$

Considering the deviation of the control quantity, the actual control quantity is:

$$\begin{cases} u(k) = u(k-1) + \Delta u(k) \\ u(k+1) = u(k) + \Delta u(k+1) \\ u(k+2) = u(k+1) + \Delta u(k+2) \\ \vdots \\ u(k+P) = u(k+P-1) + \Delta u(k+P) \end{cases} \tag{15}$$

After considering the deviation of the control quantity, the predictive value of the predictive model for the controlled object can be established as: $\boldsymbol{x}_m = \boldsymbol{x}_0 + \boldsymbol{G}\Delta\boldsymbol{u}$
Among them,

$$\boldsymbol{G} = \begin{bmatrix} \boldsymbol{B} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{AB} & \boldsymbol{B} & \boldsymbol{0} & \boldsymbol{0} \\ \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{A}^{P-1}\boldsymbol{B} & \boldsymbol{A}^{P-2}\boldsymbol{B} & \cdots & \boldsymbol{B} \end{bmatrix} \tag{16}$$

$$\boldsymbol{x}_0 = [\boldsymbol{x}_0^T(k+1|k), \boldsymbol{x}_0^T(k+2|k), \cdots, \boldsymbol{x}_0^T(k+N_P|k)] \tag{17}$$

$$\boldsymbol{x}_m = [\boldsymbol{x}_m^T(k+1|k), \boldsymbol{x}_m^T(k+2|k), \cdots, \boldsymbol{x}_m^T(k+N_P|k)] \tag{18}$$

$$\Delta\boldsymbol{u} = [\Delta\boldsymbol{u}(k), \Delta\boldsymbol{u}(k+1), \cdots, \Delta\boldsymbol{u}(k+P-1)] \tag{19}$$

The propulsion system has a maximum thrust limit of u_M : $U = \{u : \|u(t)\|_\infty \le u_M\}$

Avoid collision requirements and detection sensor field of view constraints:

$$X = \left\{x: x_1(t) \le 0, \sqrt{x_2(t)^2 + x_3(t)^2} \le -x_1(t) \cdot tan\left(\frac{\theta}{2}\right)\right\} \tag{20}$$

Where θ is the field of view of the detection sensor on the service spacecraft.

For the above-mentioned terminal guidance problem for on-orbit refuelling, the optimization index is:

$$J(x,u) = \alpha \int_{t_0}^{t_f} \|u(t)\|_1 dt + (1-\alpha) \int_{t_0}^{t_f} 1\, dt + \beta \int_{t_0}^{t_f} \varepsilon(t)\, dt \tag{21}$$

When the final time t_f is free, $\alpha \in [0,1]$ is the relative weight of fuel consumption and maneuvering time, and $\beta \ge 0$ is the weight of function ε under the plume impact requirement. The thruster plume impact function can be expressed as:

$$\varepsilon(t) = \begin{cases} u_1^-(t), & -x_1(t) \le x_{\varepsilon 1}, |x_2(t)| \le x_{\varepsilon 2}, |x_3(t)| \le x_{\varepsilon 3} \\ 0, & else \end{cases} \tag{22}$$

4. Simulation

This paper simulates the designed system, and the initial state quantity $\mathbf{x} = [x_1, \ldots, x_6] =$ [200,17,13,0,0,0].

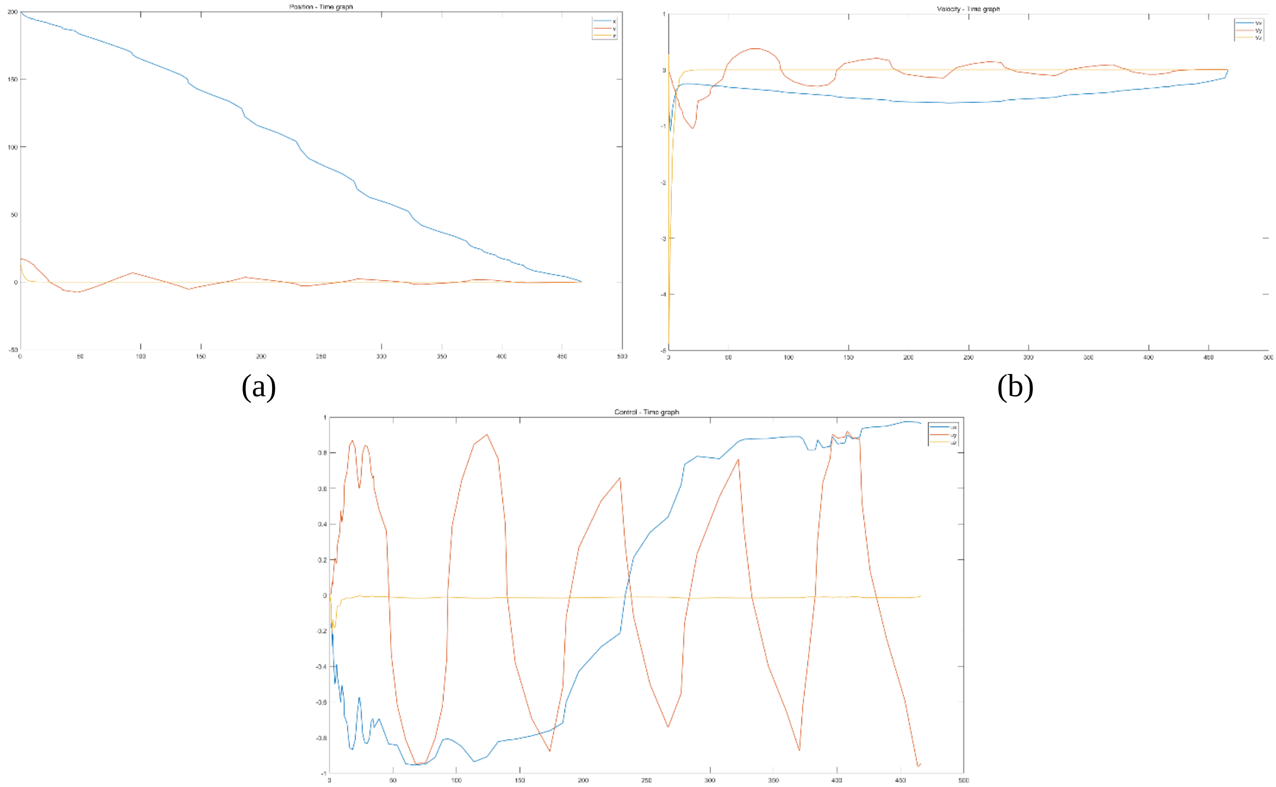

Figure 1: (a) The position of the service spacecraft relative to the target spacecraft. (b) The speed of the serving spacecraft relative to the target spacecraft. (c) Engine thrust serving the maneuvering process of the spacecraft.

As shown in the figure, after optimization, the service spacecraft can accurately and smoothly maneuver to the target spacecraft position with the minimum performance index.

5. Conclusion

This paper uses the HCW equation to establish a prediction model for spacecraft fuel in-orbit refuelling, and uses model predictive control to comprehensively optimize the maneuvering route, maneuvering speed and engine thrust of the service spacecraft, and solve the problem of the end-stage guidance of fuel on-orbit refuelling. Problems, and verify the feasibility of model predictive control in terminal guidance.

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