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Research on Autonomous Coordinated Satellite Attitude Control Algorithm of RMFFSR

Huazhong Li

School of Sino-German Robotics, Shenzhen Institute of Information Technology, Shenzhen, China

Email address:
chinawwwsl@163.com

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Abstract: Aiming at the problem of satellite attitude stability in the space operation task of redundant multi arm free floating space robot (RMFFSR), firstly, the motion model of RMFFSR is studied, and the multi arm generalized Jacobian matrix (MGJM) reflecting the motion relationship between the linear velocity and angular velocity of any manipulator end effector of RMFFSR and the angular velocity of RMFFSR joint in the free floating state is obtained. Secondly, the RMFFSR resolved motion rate control (RMRC) algorithm based on MGJM is provided. At the same time, the satellite attitude stabilization algorithm based on the MGJM for the attitude stability of multi arm coordinated satellite based on RMFFSR arbitrary manipulator and the satellite attitude stabilization algorithm based on the MGJM for the attitude stability of multi joint coordinated satellite based on RMFFSR arbitrary manipulator are researched. Finally, the RMFFSR satellite attitude control system (RSACS) is researched. By combining the multi arm manipulator planning system with the satellite body attitude control system, the motion planning with minimum attitude disturbance of the satellite body is completed; by predicting the angular momentum of the manipulator's attitude disturbance with the satellite body, the satellite body attitude control method based on the prediction of the satellite body attitude disturbance and the autonomous coordinated attitude control algorithm of the RMFFSR manipulator are realized.

Keywords: RMFFSR, Attitude Control, Coordination Control, MGJM, Attitude Disturbance Prediction, Autonomous Coordinated Attitude Control, RMRC

1. Introduction

With the development of space technology, redundant multi arm free floating space robot (RMFFSR) is more and more widely used [1-5]. Due to the free floating of the satellite in the space microgravity environment, there is a strong dynamic coupling between the satellite and the manipulator in the space manipulator system, which will make the satellite attitude difficult to maintain stability in the working process and affect the normal operation of the manipulator [6]. Aiming at the problem of attitude stability of the satellite body faced by the RMFFSR during the space operation task of capturing the target, in order to ensure the normal operation of the RMFFSR communication system and the orientation of the solar sail, it is necessary to ensure the attitude stability of the RMFFSR satellite body [7]. Cui Hao et al. studied the problem of satellite attitude adjustment through manipulator movement [8]. Zhang proposed a motion planning algorithm based on rapidly exploring random tree (RRT), which can complete the planning task without solving the inverse kinematics and retain the attitude constraints [9]. S. Dubowsky, E. E. Vance and M. A. Torres proposed the technology based on trajectory optimization, which simultaneously controls the attitude and position of the satellite body to avoid the saturation of the jet device, but consumes a lot of valuable fuel, thus shortening the on orbit life of the satellite [10]. The attitude control scheme proposed by R. Longman et al. uses the reaction wheel to provide the momentum required to only maintain the attitude of the satellite [11]. Walker et al. designed an adaptive controller to obtain global stable tracking of the end trajectory of FFSR [12]. Baoli Ma, Yangshen Xu and other scholars have studied the motion control of the manipulator when the attitude of the satellite body is stable [13, 14]. K. Yamada proposed an optimized manipulator path planning method to achieve the minimum manipulator motion required to complete the given satellite body attitude change [15]. Z. Vafa and K. Yamada proposed a self-adjusting satellite body attitude control method, which uses the unique non integrity of FFSR to adjust the satellite body attitude through the closed path motion of the manipulator in the joint space [16, 17]. C. Fernandes et al. proposed an attitude control algorithm that adjusts the attitude of the satellite body through the movement of the manipulator, but the manipulator attitude remains unchanged [18]. Y. Nakamura and R. Kukherjee studied the unique non integrity of FFSR in the free floating state, and proposed a method to convert the attitude control problem into a nonlinear control problem by using the conservation of angular momentum [19, 20]. E. Papadopoulos proposed a method to balance the reaction of the manipulator on the satellite body by using symmetry to keep the attitude of the satellite body unchanged [21]. S. Dubowsky and K. Yashida et al. proposed a method of using enhanced disturbance map (EDM) to control the movement of manipulator and minimize the interference to the attitude of satellite [22, 23]. Wu Wei optimized the EDM method [24]. D. Nenchev et al. proposed the FFSR attitude control method with fixed attitude limited Jacobian matrix to control the end of the manipulator to keep the attitude change of the satellite body to a minimum when moving along a certain path [25, 26]. K. Yoshida, S. K. Agrawal and others proposed a method to use the motion of one manipulator to compensate the influence of the motion of the other arm on the attitude of the satellite [27, 28]. Chu proposed an adaptive robust controller for variable path dynamic tracking, which can intelligently learn and compensate the unknown performance parameters in the system [29]. Wang et al. proposed a cooperative control scheme, which can correct the base attitude while tracking the optimal detumbling trajectory at the end of the manipulator [30].

Therefore, aiming at the problem of attitude stability of satellite body faced by RMFFSR in the process of space operation task of capturing target, firstly, the motion model of RMFFSR is studied, and the multi arm generalized Jacobian matrix (MGJM) describing the motion relationship between the linear velocity and angular velocity of end effector of any RMFFSR manipulator and the angular velocity of RMFFSR joint in the state of free floating is obtained. Secondly, the RMFFSR resolved motion rate control (RMRC) algorithm based on MGJM is studied. At the same time, the MGJM satellite attitude stabilization RMRC algorithm for RMFFSR multi arm coordination and the MGJM satellite attitude stabilization RMRC algorithm for RMFFSR multi joint coordination are studied. Finally, the conventional RMFFSR satellite attitude control system (RSACS) is studied, which combines the RMFFSR multi arm manipulator planning system with the satellite attitude control system. At the same time, the satellite attitude control algorithm based on RMFFSR attitude disturbance prediction and the autonomous coordinated attitude control algorithm of RMFFSR manipulator are studied.

2. Motion Modeling

According to the geometric structure of RMFFSR and the motion relationship between connecting links, the expressions of terminal linear velocity and angular velocity of the kth manipulator of RMFFSR can be obtained [22, 23]:

$$\dot{P}_E^k = r_S + \omega_S \times (P_E^k - R_S) + \sum_{i=1}^{n_k} \left[K_i^k \times \left(P_E^k - P_i^k\right)\right] \dot{\theta}_i^k \quad (1)$$

$$\omega_E^k = \omega_S + \sum_{\mathrm{i}=1}^{n_k} K_i^k \dot{\theta}_i^k \quad (2)$$

Where, $K_i^k \in R^3$ represents the unit vector of the i-th rotating joint axis of the k-th manipulator. $P_E^k \in R^3$ represents the position vector of the k-th manipulator end effector, $k \in [1, l]$.

Combined equations (1) and (2) can obtain:

$$v^k = \begin{bmatrix} \dot{P}_E^k \\ \omega_E^k \end{bmatrix} = \begin{bmatrix} E & -\tilde{P}_{SE}^k \\ 0 & E \end{bmatrix} \begin{bmatrix} \dot{r}_S \\ \omega_S \end{bmatrix} + \begin{bmatrix} J_{Mp}^k \\ J_{M\omega}^k \end{bmatrix} \dot{\Theta}_M \quad (3)$$

Where, $\Theta_\mathrm{M} = \left[\theta_1^1, \cdots \theta_{n_1}^1, \cdots, \theta_1^l, \cdots, \theta_{n_l}^l\right]^T$ represents RMFFSR joint vector space. Considering that the RMFFSR system satisfies the conservation of linear momentum P and angular momentum L at the same time, and the initial value is zero, the following can be obtained:

$$m_S \dot{r}_S + \sum_{k=1}^{l} \sum_{i=1}^{n_k} m_i^k \dot{r}_i^k \equiv 0 \quad (4)$$

$$I_S \omega_S + m_S r_S \times \dot{r}_S + \sum_{k=1}^{l} \sum_{i=1}^{n_k} (I_i^k \omega_i^k + m_i^k r_i^k \times \dot{r}_i^k) \equiv 0 \quad (5)$$

Combining formula (4) and formula (5) can obtain:

$$I_S \omega_S + I_M \dot{\Theta}_M \equiv 0 \quad (6)$$

$$\dot{\mathrm{r}}_S = J_v \dot{\Theta}_M = -\left(J_{T\omega}/W + \tilde{r}_{sg} I_S^{-1} I_M\right) \dot{\Theta}_M \quad (7)$$

Where, $I_S = I_\omega + W \tilde{r}_g \tilde{r}_{sg} \in R^{3\times3}$ represents the generalized inertia matrix of RMFFSR satellite body. $I_M = I_\Theta - \tilde{r}_g J_{T\omega} \in \mathrm{R}^{3\times n}$ represents the generalized inertia matrix of RMFFSR manipulator. Equations (6) and (7) describe the disturbance equation of the RMFFSR manipulator on the position and attitude of the satellite body.

Substitute equation (7) into equation (3) to obtain:

$$v^k = \begin{bmatrix} -\tilde{P}_{SE}^k \\ E \end{bmatrix} \omega_S + \begin{bmatrix} J_v + J_{Mp}^k \\ J_{M\omega}^k \end{bmatrix} \dot{\Theta}_M = J_S^k \omega_S + J_M^k \dot{\Theta}_M \quad (8)$$

Where, ω_S can be obtained from (6):

$$\omega_S = -I_S^{-1} I_M \dot{\Theta}_M = J_\omega \dot{\Theta}_M \quad (9)$$

Replace equation (9) with equation (8) to obtain:

$$v^k = (J_M^k - J_S^k I_S^{-1} I_M) \dot{\Theta}_M = J_G^k \dot{\Theta}_M, k \in [1, l] \quad (10)$$

Where, J_G^k is the generalized Jacobian matrix of the motion velocity of the end effector of the kth manipulator of RMFFSR, which reflects the motion relationship between the linear velocity and angular velocity of the end effector of the kth manipulator and the angular velocity of the joint of RMFFSR under the free floating state of the satellite body.

3. Multi Arm Coordinated Motion Control for Satellite Attitude Stabilization

3.1. RMFFSR Resolved Motion Rate Control

How to control the manipulator of RMFFSR to track the given target trajectory according to the given speed and satellite attitude is the main key technology of RMFFSR in space operation.

This paper adopts a typical resolved motion rate control (RMRC) method. The RMRC studied in this paper is a continuous motion trajectory tracking control algorithm based on multi arm generalized Jacobian matrix (MGJM).

On the one hand, the kinematics problem can be linearized by using multi arm generalized Jacobian matrix (MGJM), which can be solved only by calculating the inverse MGJM. If the initial state of RMFFSR and every step of joint motion can be known, the position and direction trajectory of RMFFSR end effector in Cartesian inertial space can be obtained through numerical calculation.

On the other hand, it is easy to add the law of momentum conservation by using the resolved motion rate control (RMRC), so that the reaction effect of RMFFSR system can be described only by motion speed and momentum without considering acceleration and force.

Write equation (10) into matrix form to obtain:

$$v = J_{GJM} \cdot \dot{\Theta}_M \tag{11}$$

Where, $v = [v^1, v^2, \cdots, v^l]^T, J_{GJM} = [J_G^1, J_G^2, \cdots, J_G^l]^T$.

From equations (10) and (11) respectively:

$$\dot{\Theta}_M = [J_G^k]^+ v_d^k, k \in [1, l] \tag{12}$$

$$\dot{\Theta}_M = [J_{GJM}]^+ v_d \tag{13}$$

Where, v_d^k is the desired linear velocity and angular velocity of the end effector of the kth manipulator of RMFFSR. v_d is the desired linear velocity and angular velocity of all manipulator end effectors of RMFFSR. $\dot{\Theta}_M$ is the angular velocity control vector of RMFFSR joint. Since the calculation formula of MGJM already includes the interaction between RMFFSR satellite body and manipulator, the resolved motion rate control (RMRC) method based on multi arm generalized Jacobian matrix (MGJM) can overcome the influence of RMFFSR satellite body position and attitude motion in Cartesian inertial coordinate system, The end effector of redundant multi arm free floating space robot (RMFFSR) manipulator is strictly controlled to move along the planned trajectory.

For redundant multi arm free floating space robot (RMFFSR), the attitude coordination control problem of satellite body can be described as: By coordinating the motion v^k of the end effector of the RMFFSR manipulator and the attitude angular velocity ω_S of the satellite body, $\omega_S = 0$ is expected when the manipulator moves, so as to maintain the attitude stability of the RMFFSR satellite body.

Therefore, substituting $\omega_S = 0$ into equations (6) and (8) can obtain the attitude disturbance characteristics of RMFFSR, the end effector velocity of the kth manipulator and the angular velocity of each joint of RMFFSR manipulator respectively:

$$I_M \dot{\Theta}_M \equiv 0 \tag{14}$$

$$v^k = J_M^k \dot{\Theta}_M, k \in [1, l] \tag{15}$$

The algorithm for planning the motion of redundant multi arm free floating space robot (RMFFSR) manipulator by using resolved motion rate control (RMRC) is described as follows.

Algorithm 1 RMRC algorithm of RMFFSR manipulator.

Step 1. Input the initial state of RMFFSR. According to the parameters of RMFFSR, the workspace of RMFFSR manipulator is calculated. Speed decomposition according to the given path in RMFFSR workspace. Set the desired speed of the end effector of the RMFFSR manipulator $v_d^k(i)(i = 0, 1, \cdots, N-1)$. The position and attitude of the RMFFSR satellite body are $r_S(0)$ and $\Phi_S(0)$ respectively. The joint angle vector is $\Theta_{\mathrm{M}}(0)$. Set loop variable to zero $= 0$.

Step 2. Calculate $\dot{\Theta}_M^k(i) = [J_{GJM}^k]^+ v_d^k(i)$. If $|\dot{\Theta}_M^k(i)| > \dot{\Theta}_{MMax}^k$, then $\dot{\Theta}_M^k(i) = \mathrm{sign}(\dot{\Theta}_M^k(i))|\dot{\Theta}_{MMax}^k|$. Among them, $\dot{\Theta}_{MMax}^k$ is the maximum joint motion speed of the kth manipulator of RMFFSR.

Step 3. Drive the joints of RMFFSR manipulator according to $\dot{\Theta}_M^k(i)$.

Step 4. Calculate the new status of RMFFSR:

(1) Calculate the new position of RMFFSR satellite body $r_S(i+1) = r_S(i) + \Delta r_S$.

(2) Calculate the attitude angle of RMFFSR satellite body $\Phi_S(i+1) = \Phi_S(i) + \Delta\Phi_S$.

(3) Calculate the joint angle of each joint of RMFFSR: $\Theta_M^k(\mathrm{i}+1) = \Theta_M^k(i) + \dot{\Theta}_M^k \cdot \Delta t$.

Step 5. If i=N, go to step 6; otherwise, i=i+1, go to step 2.

Step 6. The algorithm ends.

It should be noted that, when solving the pseudo inverse $[J_{GJM}^k]^+$ of J_{GJM}, it is possible to get the least squares solution. At this time, the RMFFSR manipulator is in a strange state and cannot plan the movement of the RMFFSR manipulator as required.

3.2. RMFFSR Multi Joint Coordinated Motion Planning

At this time, the joint space of RMFFSR is considered as a whole. When the k-th manipulator of RMFFSR completes a given task, multi joint coordinated motion is carried out in the whole RMFFSR joint space, so that RMFFSR will not produce attitude disturbance to the satellite body during operation. According to equation (14), the redundant pseudo inverse formula can be used to obtain:

$$\dot{\Theta}_M = (I - I_M^+ I_M)\dot{\Theta},\ \forall \Theta \in R^n \tag{16}$$

Where, any vector Θ can be obtained by other constraints. The goal of this paper is to plan that when the k-th manipulator of RMFFSR moves along a given trajectory, it will not produce attitude disturbance to the satellite body. Replace equation (16) with equation (15) to obtain:

$$v^k = J_M^k (I - I_M^+ I_M)\dot{\theta}, k \in [1, l] \quad (17)$$

$\dot{\theta}$ can be obtained from equation (17).

$$\dot{\theta} = [J_M^k (I - I_M^+ I_M)]^+ v^k \quad (18)$$

Substitute equation (18) into equation (16) to obtain:

$$\dot{\Theta}_M = [J_M^k (I - I_M^+ I_M)]^+ \cdot v^k = [J_{AZG}^k]^+ \cdot v^k \quad (19)$$

Where, J_{AZG}^k is the generalized Jacobian matrix(GJM) of satellite attitude stability for the whole joint space of the kth manipulator of RMFFSR. The physical meaning of J_{AZG}^k represents the relationship between the velocity of the end effector of the kth manipulator of RMFFSR and the velocity of the whole joint space when maintaining the satellite attitude stability. Therefore, the resolved motion rate control (RMRC) of RMFFSR completed by J_{AZG}^k ensures that the motion of the kth manipulator of RMFFSR will not interfere with the attitude of the satellite body, so as to complete the coordinated motion of the kth manipulator of RMFFSR and the satellite body.

3.3. RMFFSR Multi Arm Coordinated Motion Planning

At this time, the joint space of RMFFSR is regarded as composed of the joint angles of each manipulator. When the k-th manipulator of RMFFSR completes the given task, other manipulators of RMFFSR are used to coordinate the movement, so that the attitude interference of the satellite body will not be generated during space operation. From equation (14) and equation (15):

$$I_M \dot{\Theta}_M = \sum_{k=1}^{l} I_M^k \dot{\Theta}_M^k = I_M^k \dot{\Theta}_M^k + I_M^{l-k} \dot{\Theta}_M^{l-k} = 0 \quad (20)$$

$$v^k = J_M^k \dot{\Theta}_M = \sum_{j=1}^{l} J_M^{k,j} \dot{\Theta}_M^j = J_M^{k,k} \dot{\Theta}_M^k + J_M^{k,l-k} \dot{\Theta}_M^{l-k} \quad (21)$$

Where, I_M^k and $J_M^{k,k}$ are the submatrix formed by the part corresponding to the joint angle of the kth manipulator of RMFFSR in I_M and J_M^k, respectively. I_M^{l-k} and $J_M^{k,l-k}$ are sub matrices formed by removing the part corresponding to the joint angle of the k-th manipulator of RMFFSR in matrices I_M and J_M^k, respectively. From equation (20):

$$\dot{\Theta}_M^{l-k} = -[I_M^{l-k}]^+ I_M^k \dot{\Theta}_M^k \quad (22)$$

Substituting equation (22) into equation (21) can obtain:

$$v^k = \left(J_M^{k,k} - J_M^{k,l-k} [I_M^{l-k}]^+ I_M^k\right) \dot{\Theta}_M^k = J_{ARG}^k \dot{\Theta}_M^k \quad (23)$$

Where, J_{ARG}^k is the generalized Jacobian matrix of the k-th manipulator of RMFFSR for attitude stability of multi arm coordinated satellite. Firstly, J_{ARG}^k can be used to plan the motion of the k-th manipulator in the joint space, and then equation (22) can be used to solve the coordinated motion of other manipulators, so as to realize the RMFFSR motion planning to maintain the stability of satellite attitude.

3.4. Satellite Attitude Stabilization RMRC

The Jacobian matrix J_{AZG}^k or J_{ARG}^k of the attitude stability of the satellite body describes the relationship between the motion speed of the end effector of the kth manipulator of RMFFSR and the joint angular speed at the speed level, so it can also be applied to the resolved motion rate control (RMRC). According to equation (23):

$$\dot{\Theta}_M^k = [J_{ARG}^k]^+ v_d^k \quad (24)$$

Substitute $\dot{\Theta}_M^k$ into equation (22) and obtain $\dot{\Theta}_M^{l-k}$ to obtain $\dot{\Theta}_M$, which is the RMFFSR joint angular velocity control vector without disturbance to the satellite body.

If the trajectory and speed given by the end effector of multiple manipulators are tracked at the same time, the solution method of J_{ARG}^k can be followed. Similarly, the resolved motion rate control (RMRC) based on multi arm coordination of multiple manipulators of RMFFSR can be obtained.

For the redundant multi arm free floating space robot (RMFFSR) system studied in this paper, Lyapunov method can be used to avoid the dynamic singularity of RMFFSR. Let P_{Ef}^k be the desired position of the end of the RMFFSR manipulator, and design the motion law of the joint angles Θ_M.

$$\dot{\Theta}_M^* = [J_{ARG}^k]^+ A_v \left(P_{Ef}^k - P_E^k\right) \quad (25)$$

$$\dot{\Theta}_M = \begin{cases} \dot{\Theta}_M^* & , \left|\dot{\Theta}_M^*\right| \le \dot{\Theta}_{MMax} \\ sign(\dot{\Theta}_M^*) \Theta_{MMax} & , \left|\dot{\Theta}_M^*\right| > \dot{\Theta}_{MMax} \end{cases} \quad (26)$$

The motion planning of the RMFFSR capturing the target in the free floating state requires that the RMFFSR manipulator can accurately capture the target and maintain the attitude of the RMFFSR satellite, therefore, the RMRC method of satellite body attitude stabilization RMFFSR based on J_{ARG}^k can be adopted.

Algorithm 2 RMFFSR manipulator k capture target motion planning algorithm.

Step 1. Input the initial status information of RMFFSR. According to the geometric and physical parameters of RMFFSR, the workspace of RMFFSR manipulator k is calculated. Set the target position as P_t. The position and attitude of RMFFSR satellite body are $r_S(0)$ and $\Phi_S(0)$ respectively.

Step 2. If the target location P_t is not in the RMFFSR workspace, it cannot be captured, and go to step 11.

Step 3. Adjust the attitude of RMFFSR satellite body to make P_t enter the acquisition range. Set i=0.

Step 4. Calculate the position $P_E^k(\mathrm{i})$. of the effector at the k end of the RMFFSR manipulator.

Step 5. If $P_E^k(\mathrm{i}) = P_t$, RMFFSR successfully captures the target, and go to step 11.

Step 6. The motion velocity is decomposed along the motion trajectory to obtain $v_d^k = \left(P_t - P_E^k(\mathrm{i})\right)/(\mathrm{n} \cdot \Delta\mathrm{t})$ in the next step. Where, $\Delta\mathrm{t}$ is the control cycle and n is the total number of steps. If v_d^k is too large, the subdivision path can be further increased.

Step 7. Calculate $\dot{\Theta}_M^k(i) = [J_{ARG}^k]^+ v_d^k(i)$. If $|\dot{\Theta}_M^k(i)| > \dot{\Theta}_{MMax}^k$, then $\dot{\Theta}_M^k(i) = \text{sign}(\dot{\Theta}_M^k(i))|\dot{\Theta}_{MMax}^k|$. Where, $\dot{\Theta}_{MMax}^k$ is the maximum joint motion speed of the kth manipulator of RMFFSR.

Step 8. Use equation (22) to solve the corresponding $\dot{\Theta}_M^{l-k} = -[I_M^{l-k}]^+ I_M^k \dot{\Theta}_M^k$. Drive the joints of RMFFSR manipulator according to $\dot{\Theta}_M(\text{i})$.

Step 9. Calculate the new status of RMFFSR:

(1) Calculate the new position $r_S(i+1) = r_S(i) + \Delta r_S$ of the RMFFSR satellite body.

(2) Calculate the attitude angle $\Phi_S(i+1) = \Phi_S(i) + \Delta\Phi_S$ of the RMFFSR satellite body.

(3) Calculate the joint angle $\Theta_M^k(\text{i}+1) = \Theta_M^k(i) + \dot{\Theta}_M^k \cdot \Delta t$ of each joint of RMFFSR.

(4) Calculate the new position of the k-th manipulator end effector of RMFFSR.

Step 10. $i = i + 1$, turn to step 5.

Step 11. The algorithm ends.

The following points should be noted in the above algorithm:

(1) Select the appropriate control cycle Δt. The resolved motion rate control (RMRC) method realizes the motion control of the RMFFSR manipulator by outputting the angular velocity of each joint of the RMFFSR manipulator in each control cycle. If the control period Δt is too large, the accuracy of RMFFSR motion control is difficult to meet the requirements. If the control period Δt is too small, the pseudo inverse $[J_{ARG}^k]^+$ of the Jacobian matrix J_{ARG}^k for the attitude stability of the satellite body must be calculated in each period, which makes it difficult for real-time control.

(2) In step 7, when $v_d^k \notin \text{R}(J_{ARG}^k)$, the least square solution is obtained according to equation (24), and the RMFFSR manipulator is in a singular state. At this time, you can consider selecting this solution, or selecting $\dot{\Theta}_M^k$ obtained in the previous control cycle to control the movement of the RMFFSR manipulator. At this time, the attitude of the RMFFSR satellite body will change, so you need to use the following attitude control method to re correct the attitude of the satellite body.

(3) In step 7, the limitation of joint angular velocity of RMFFSR manipulator should also be considered.

(4) In step 9, the limitation of joint angle of RMFFSR manipulator should be considered.

4. Satellite Attitude Control of RMFFSR

It can be seen from the above research that theoretically, the RMFFSR can eliminate its attitude interference to the satellite body through multi arm coordinated motion planning, but when the RMFFSR system encounters kinematic and dynamic singularity problems, it will inevitably interfere with the attitude of the satellite body, at this time, RMFFSR satellite attitude control system (RSACS) must be used to maintain the stability of satellite attitude.

4.1. Conventional RSACS

The satellite body of RMFFSR must establish and maintain a certain attitude to ensure the normal operation of the communication system of RMFFSR and the orientation of the solar sail. Therefore, attitude control is required. RMFFSR satellite attitude control system (RSACS) is a closed-loop control system composed of attitude sensor, satellite attitude controller and RMFFSR satellite body dynamic physical model.

(1) The attitude sensor is responsible for directly measuring the direction of a selected target or satellite body in the Cartesian inertial coordinate system or the information related to the direction. After comparison and calculation, the state of the target or satellite body in the spatial reference system is obtained.

(2) The attitude controller of satellite body is mainly responsible for controlling signal processing and torque actuator. Air injection and magnetic control belong to external torque control; The flywheel motor belongs to internal force control. Using the angular momentum exchange between various flywheels and the satellite body is the main mode of attitude stability control of the satellite body.

At present, RMFFSR mostly adopts three-axis attitude control system for satellite body attitude control. Their angular momentum is parallel to the main inertia axis of the satellite body and independently absorbs the external angular momentum along the rolling, pitching and yaw axes. The satellite body attitude control system adjusts the rotational speed of the flywheel according to the attitude deviation on the side of the attitude sensor to realize continuous satellite body attitude control.

According to the dynamic characteristics, the attitude control system of three-axis satellite body is divided into two categories:

(1) Zero momentum system. The internal momentum moment of the system is zero or very small, so it does not have the property of gyro axis determination. Its characteristic is that when the attitude error is very small, the control of the three attitude axes is independent.

(2) Bias momentum system. High speed flywheel with gyro fixed axis inside. It is characterized by mutual coupling among three axes and slow response speed (out of the direction of disturbance moment).

Existing research shows that the three-axis RMFFSR satellite body attitude control system (RSACS) can effectively maintain the stability of the satellite body attitude by making the flywheel speed return to its initial attitude in the opposite direction, and release the external interference momentum stored in the flywheel, so that the flywheel can absorb the external interference momentum again to achieve the desaturation function of the flywheel. If the external disturbance torque is greater than the adjustment limit of the reaction flywheel, the attitude of the satellite will be directly controlled by the jet equipment.

Obviously, the satellite attitude control method can eliminate the interference caused by the movement of redundant RMFFSR manipulator to the satellite body attitude; It can also eliminate the attitude problems caused by the inaccurate geometric parameters and inertial parameters of redundant RMFFSR, but this method does not make full use of the prediction information of RMFFSR manipulator, which will consume a lot of attitude control fuel and significantly shorten the on orbit life of the satellite.

It can be seen that during the movement of the RMFFSR manipulator, the interference to the satellite body should be minimized to avoid flywheel saturation, thus consuming the fuel used by jet equipment.

4.2. Satellite Attitude Control Based on RMFFSR Attitude Disturbance Prediction

By introducing the RMFFSR satellite body attitude control method based on attitude interference prediction, the reaction force generated by the RMFFSR manipulator on the satellite body attitude interference is estimated and transmitted to the satellite body attitude control system to complete the feedforward control compensation, so as to improve the overall performance of the satellite body attitude control system. The form of reaction force can be estimated by either reaction moment or reaction angular momentum.

Therefore, in the attitude control of RMFFSR satellite body attitude control system, the reaction wheel can be used to generate the control torque or control angular momentum. RSACS uses the data measured by the attitude sensor to complete the closed-loop control.

Considering the physical significance of the law of conservation of momentum, this paper calculates the angular momentum increment of RMFFSR manipulator, that is, the reaction angular momentum it produces on the satellite body, as shown in formula (27).

$$\Delta \mathrm{L} = L_M(t_{i+1}) - L_M(t_i) \tag{27}$$

Where, $L_M(t) = \sum_{k=1}^{l}\sum_{i=1}^{n_k}\left(I_i^k\omega_i^k + m_i^k r_i^k \times \dot{r}_i^k\right)$ represents the angular momentum of the RMFFSR manipulator at time t.

When the RMFFSR manipulator moves, RSACS will use the estimated value of reaction angular momentum ΔL provided by the RMFFSR manipulator motion control system for feedforward control, and use the output of attitude sensor for feedback control to jointly maintain the attitude stability of the satellite body. The state of attitude control, such as the attitude of the satellite, the motion rate and the control state of the reaction wheel, can be provided to the RMFFSR manipulator motion control system to correct its motion planning.

The essence of feedback control system is that after the object is disturbed, it must react according to the size of system output deviation when the controlled quantity deviates, so as to compensate the influence of interference on the controlled quantity. Therefore, feedback control itself determines that the interference cannot be overcome before the controlled quantity deviates from the set value, which limits the further improvement of control quality. However, by introducing feedforward control into the control system, that is, controlling directly according to the disturbance, the controller will play a role before the controlled quantity shows change, so as to overcome the shortcomings of feedback control. Therefore, the combination of feedforward and feedback control can not only reduce the steady-state error of the system, but also ensure the stability of the system.

4.3. RMFFSR Satellite Attitude Controlled RMRC Algorithm

The reaction wheel or jet device is used to control the attitude of the RMFFSR satellite body to keep its attitude unchanged, while the position of the RMFFSR satellite body can float freely, which can be obtained from equation (8):

$$\upsilon^k = J_S^k\omega_S + J_M^k\dot{\Theta}_M \tag{28}$$

Due to the role of RMFFSR satellite attitude control system (RSACS), it can be considered that $\omega_S = 0$ can be obtained by substituting into equation (28):

$$\upsilon^k = J_M^k\dot{\Theta}_M \tag{29}$$

Where, J_M^k is called satellite attitude controlled generalized Jacobian matrix, which is different from the Jacobian matrix J_{AZG}^k or J_{ARG}^k of satellite attitude stability. The main difference between the two is that the motion of the RMFFSR manipulator described by the satellite attitude controlled generalized Jacobian matrix J_M^k will interfere with the satellite body, but the attitude of the satellite body will not change due to the activation of RSACS. The motion of the redundant RMFFSR manipulator described by the Jacobian matrix J_{AZG}^k or J_{ARG}^k of the attitude stability of the satellite body will not cause attitude interference to the satellite body in theory, so the attitude of the satellite body will not change.

From equation (29):

$$\dot{\Theta}_M = [J_M^k]^{+}\upsilon^k \tag{30}$$

Where, $[J_M^k]^{+}$ is the pseudo inverse matrix of J_M^k. According to equation (30), the attitude controlled RMRC algorithm of RMFFSR satellite can be realized.

4.4. Autonomous Coordinated Attitude Control of RMFFSR Manipulator

Aiming at the redundant multi arm free floating space robot (RMFFSR) manipulator completing a space operation to capture the target, an autonomous coordinated attitude control algorithm of RMFFSR manipulator is proposed to adopt different attitude control and motion control strategies in different operation stages and different situations.

Algorithm 3 Autonomous coordinated attitude control algorithm of RMFFSR manipulator.

Step 1. Input the initial pose information of RMFFSR and target.

Step 2. Calculate the workspace of the kth manipulator of RMFFSR according to the geometric and physical parameters of RMFFSR. Set the target position as P_t, and the position and attitude of RMFFSR satellite body are $r_S(0)$ and $\Phi_S(0)$ respectively The joint angle vector is $\Theta_{\mathrm{M}}(0)$.

Step 3. If the target position P_t is in the RMFFSR workspace, go to step 8.

Step 4. Select the rendezvous point and plan the flight path of RMFFSR.

Step 5. Close the RMFFSR multi manipulator, start the jet equipment and RSACS attitude control system, and approach the rendezvous point.

Step 6. After reaching the rendezvous point, close the jet device and RSACS attitude control system, enter the free floating state, and the redundant RMFFSR manipulator moves symmetrically to restore the initial optimal configuration.

Step 7. Recalculate J_{ARG}^k with the new parameters.

Step 8. Algorithm 2 is used to plan the motion of RMFFSR manipulator and control a manipulator of RMFFSR to capture the target.

Step 9. Judge whether other mechanical arms of RMFFSR complete the task. If completed, go to step 12.

Step 10. Judge whether the system has redundancy in the new task space according to the requirements of the system for the operation of the manipulator. If there is redundancy, go to step 12.

Step 11. Use the satellite attitude controlled generalized Jacobian matrix J_M^k to plan the motion of the RMFFSR manipulator, estimate its disturbance angular momentum ΔL to the satellite body according to equation (27), drive the RMFFSR manipulator to move, start the feedforward attitude controller based on attitude interference prediction for feedforward control, start the feedback attitude control system at the same time, and use the output of the attitude sensor for feedback control to jointly maintain the attitude stability of the satellite body. Go to step 9.

Step 12. The motion of the redundant RMFFSR manipulator is planned by using the Jacobian matrix J_{AZG}^k or J_{ARG}^k with stable attitude of the satellite body. The RMFFSR manipulator is driven to move, and the RSACS attitude control system is used to control the satellite attitude error in actual work.

Step 13. The algorithm ends.

5. Conclusion

Aiming at the attitude stability problem of satellite body faced by RMFFSR, firstly, the motion model of RMFFSR is studied. Secondly, RMFFSR RMRC algorithm based on MGJM and RMRC algorithm of MGJM satellite attitude stabilization coordinated by RMFFSR are researched. Finally, the satellite attitude control algorithm based on RMFFSR attitude disturbance prediction and the autonomous coordinated attitude control algorithm of RMFFSR manipulator are proposed.

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