Research Article: Open Access

DOI: 10.35840/2631-5009/7565

VIBGYOR ePress

International Journal of
Astronautics and Aeronautical Engineering

Non-Holonomic Path Planning for Space Robots Based on Jerk Constraints

ISSN: 2631-5009

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Summary

In order to solve the problems of poor stability and low joint life of space robots, this paper proposes a non-holonomic path planning model for free-flying space robots considering jerk constraints. Firstly, the attitude of the space robot is described by the unit quaternion, through the analysis of the differential motion equation of the space robot, the velocity relations among the base, joint angle, and the end-effector are established. Secondly, the joint trajectories were parameterized by the seventh-order sinusoidal function. Then, according to the jerk constraint, the precision of the pedestal disturbance, and the task completion time, the optimal path planning model of the pedestal disturbance and time synthesis is proposed. Finally, the particle swarm optimization algorithm is used to solve the optimal path optimization problem of the space robot. The simulation results show that the proposed trajectory planning method effectively solves the problems of low maintenance efficiency and large base disturbance of the space robot under jerk constraints.

Keywords

Space robot, Jerk, Trajectory optimization, Base disturbance, Non-holonomic path planning

Introduction

With more and more types of space equipment, damage to spacecraft equipment occurs every year due to component failures. After some spacecraft are launched into orbit, problems such as component failure and orbit deviation may occur [1-3]. While some spacecraft complete their scheduled missions and run out of fuel, their main structures and components can still function normally, at this time, through the space robot for in-orbit maintenance, the fuel supply and component replacement can make the failure of the spacecraft to return to normal operation, prolong the service life of the spacecraft, increase economic benefits. In addition, some large-scale complex structured space equipment has appeared one after another. In the future, space robots can be used to repair large-scale equipment in orbit to provide guarantee for the normal operation of space missions.

Space robot is one of the main ways to achieve on-orbit maintenance. Space operating devices cannot operate normally due to faults, aging and other reasons. In order to enhance the service life of space

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Accepted: May 17, 2023; **Published:** May 19, 2023

Citation: Xiao P, Zhou J, Zhou C, Si Y, Zhou D (2023) Non-Holonomic Path Planning for Space Robots Based on Jerk Constraints. Int J Astronaut Aeronautical Eng 8:065

equipment, the space robot is used to complete the maintenance tasks of all kinds of space equipment through on-orbit operation. Because of the particularity of space robot, it has been studied and concerned by many scholars [4-9]. The motion of the space manipulator will affect the position and attitude of the base, and the change of the base pose of the space robot will in turn affect the accuracy of the end-effector of the space robot, leading to the failure of the maintenance task. After the space robot completes the capture task, the base attitude of the space robot changes due to the dynamic coupling effect. Based on the non-holonomic characteristics of the space robot, the path planning is carried out. By controlling the motion of the joint of the manipulator, the joint angle and the base attitude angle of the manipulator converge to the desired state simultaneously [10,11].

Dubowsky and Torres [12] proposed an enhanced perturbation mapping technique to plan the motion of the space manipulator, so that the perturbation of the base attitude was relatively small. Yoshida [13] focused on the planning and control of the manipulator using the generalized Jacobian matrix and the concept of reaction null space. Huang [14] proposed an optimal path planning method based on genetic algorithm (GA) with minimum base reaction interference, but the implementation of the genetic algorithm is relatively complex. Xu [15] adjusted the attitude of the base by adjusting the joint angle on the basis of estimating the reaction force of the joint motion of the manipulator on the base. Papadopoulos [16] used polynomial functions to carry out path planning for the manipulator, and by controlling the movement of the manipulator, the end pose of the manipulator and the attitude of the base can reach the desired goal at the same time. Yoshida, et al. [17] studied the free motion law of both arms and proposed the concept of two-arm coordination. The motion of one manipulator arm was used to compensate the influence of the motion of another manipulator arm on the attitude of the base. Wang [18] used the concept of reaction null space to describe the motion law of robot in free-floating space, and adopted Bezier curve to describe the joint trajectory. Cocuzza and Pretto [19] proposed a redundancy decomposition method based on constrained least squares to ensure that the disturbance of the space manipulator base is minimized. Liu and Jia [20] proposed a maximum load trajectory planning method based on multi-objective optimization for a space robot carrying heavy loads to move to the desired pose. Oda [21] proposed the coordinated control between the satellite attitude control system and the manipulator control system, which required the simultaneous control of the satellite attitude and the joint of the manipulator, but this would consume more control fuel. Huang and Xu [22] developed a space robot system that consists of two arms, one of which is used to complete the capture task and the other is used to compensate the interference of the base, but this method increases the complexity of the system. Park [23] used a mixed function of Fourier and polynomials to describe the trajectory, and used motion planning to optimize the residual vibration of the robot.

Non-holonomic path planning is to adjust the attitude of the base by controlling the movement of the manipulator without consuming fuel. At present, researches on non-holonomic path planning of space robots are extensive [24-27], but the situation of space jerk is not considered. Space robots have high requirements for flexibility, stability and efficiency, and the conservation of linear momentum and angular momentum should be considered. In this paper, a jerk-based space robot trajectory planning model is established based on the existing research methods, which can ensure that the space manipulator meets the high efficiency and base stability.

The rest of this article is arranged as follows: In Section 2, the symbolic representation and theoretical basis of space robots are introduced. In Section 3, the Cartesian space trajectory planning problem is analyzed, and the joint trajectory is parameterized by sinusoidal function curve, and the objective function and constraint conditions of the planning are analyzed in detail. In Section 4, the particle swarm optimization algorithm is proposed to solve the non-holonomic path planning of space robot based on jerk constraints. In section 5, the feasibility of the plan is verified by experimental simulation and the results are discussed. Section 6 provides the conclusion.

Theoretical Foundation of Space Robot System Modeling

Space robot model and symbolic representation

The model of the space robot is shown in Figure 1, which is composed of a space manipulator and a

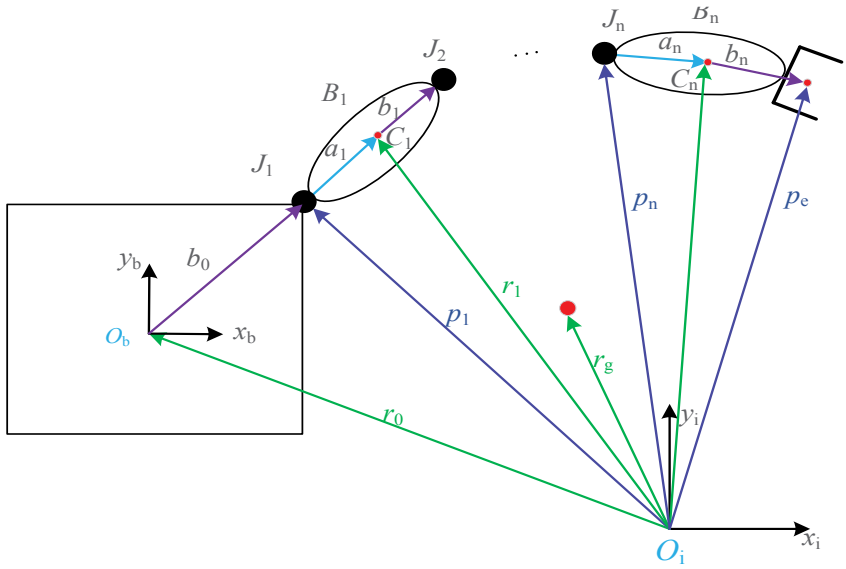

Figure 1: The model of the space robot.

spacecraft base platform. Define the base of the spacecraft as rigid body B_0, the ith link of the manipulator is rigid body B_i, the joint connecting rigid body B_{i-1} and rigid body B_i is J_i, the center of mass of rigid body i is m_i, the mass of rigid body i is m_i, the total mass of the system is M, and the moment of inertia of the rigid body i to its center of mass is $\boldsymbol{I}_i$.

If there is no special indication in this article, they are all indicated under the inertial system.

The position vector of the end of the manipulator is denoted as $\boldsymbol{p}_e$, the position vector of the center of mass of the rigid body B_i is denoted as $\boldsymbol{r}_i$, the unit vector of the rotation axis of joint J_i is denoted as $\boldsymbol{n}_i$, the position vector from J_i to C_i is denoted as $\boldsymbol{a}_i$, and the position vector from C_i to J_{i+1} is denoted as $\boldsymbol{b}_i$.

Kinematics equation of space robot

The position vector of the end of space robot can be expressed as:

$$\boldsymbol{p}_e = \boldsymbol{r}_0 + \boldsymbol{b}_0 + \sum_{k=1}^{n} \left(\boldsymbol{a}_k + \boldsymbol{b}_k \right) \tag{1}$$

The linear velocity at the end is expressed as

$$\boldsymbol{v}_e = \boldsymbol{v}_0 + \boldsymbol{w}_0 \times \left(\boldsymbol{r}_i - \boldsymbol{r}_0 \right) + \sum_{=1} \left[\boldsymbol{n}_k \times \left(\boldsymbol{p}_e - \boldsymbol{p}_k \right) \right]_k \tag{2}$$

The angular velocity at the end is expressed as

$$\boldsymbol{w}_e = \boldsymbol{w}_0 + \sum_{k=1}^{n} \boldsymbol{n}_k \dot{\theta}_k \tag{3}$$

The linear velocity and angular velocity of the end effector of the space robot can be uniformly expressed in the form of a matrix as:

$$\dot{\boldsymbol{x}}_e = \begin{bmatrix} \boldsymbol{v}_e \\ \boldsymbol{w}_e \end{bmatrix} = \boldsymbol{J}_b \dot{\boldsymbol{x}}_0 + \boldsymbol{J}_m \dot{\theta} \tag{4}$$

Where $\boldsymbol{J}_b$ is the Jacobian matrix related to the movement of the base, $\boldsymbol{J}_m$ is the Jacobian matrix related to the motion of the manipulator, $\boldsymbol{\vartheta}$ is the joint angle vector.

The position and attitude of the base of the space robot are not controlled. When it is not affected by external forces and moments, the linear momentum and angular momentum of the system are conserved. Assuming that their initial values are zero, the momentum conservation equation of the center of mass of

the base satisfies the following constraints:

$$\begin{bmatrix} \boldsymbol{P} \\ \boldsymbol{L} \end{bmatrix} = \begin{bmatrix} \sum_{i=0}^{n} m_i \dot{\boldsymbol{r}}_i \\ \sum_{i=0}^{n} \left(\boldsymbol{I}_i \omega_i + \boldsymbol{r}_i \times m_i \dot{\boldsymbol{r}}_i \right) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{5}$$

According to the equation (5),

$$\boldsymbol{H}_b \dot{\boldsymbol{x}}_b + \boldsymbol{H}_{bm} \dot{\theta} = 0 \tag{6}$$

then

$$\dot{\boldsymbol{x}}_b = \boldsymbol{H}_b^{-1} \boldsymbol{H}_{bm} \dot{\theta} = \boldsymbol{J}_{bm} \dot{\theta} = \begin{bmatrix} \boldsymbol{J}_{bm\_v} \\ \boldsymbol{J}_{bm\_w} \end{bmatrix} \dot{\theta} \tag{7}$$

The matrix $\boldsymbol{J}_{bm}$ is the base-manipulator Jacobian matrix.

Quaternion representation of rigid body attitude

There are Euler angle, axis-angle, rotation transformation matrix and unit quaternion methods to describe the attitude of rigid body. Among them, when using Euler angles and axis-angle methods to describe the attitude, it is easy to produce singular phenomena. The rotation matrix must satisfy the constraint of orthogonal normalization. When this constraint cannot be satisfied, the rotation matrix will be ill-conditioned and the calculation error will be relatively large. However, the use of unit quaternion can avoid these problems. The module of unit quaternion is 1, which has stronger robustness relative to the ill-conditioned rotation transformation matrix. There is a one-to-one mapping relationship between unit quaternion and attitude, so the singularity can be avoided.

The representation of the unit quaternion is shown below

$$\boldsymbol{Q} = [\eta,\ \boldsymbol{q}]^{\mathrm{T}} = \left[\cos\frac{\psi}{2},\ \boldsymbol{n} \cdot \sin\frac{\psi}{2} \right]^{\mathrm{T}} \tag{8}$$

Among them, $\boldsymbol{q}$ is the rotation axis, which is the unit vector, and ψ is the angle of rotation around the rotation axis.

The relationship between the time derivative of the unit quaternion and the angular velocity is as follows

$$\begin{bmatrix} \dot{\eta} \\ \dot{\boldsymbol{q}} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} -\boldsymbol{q} \\ \eta \boldsymbol{1} - \tilde{\boldsymbol{q}} \end{bmatrix} \boldsymbol{w} \tag{9}$$

Among them, $\tilde{\boldsymbol{q}}$ is the antisymmetric matrix of $\boldsymbol{q}$, and $\boldsymbol{1}$ is the identity matrix.

Consider two coordinate systems, the attitude quaternions are $\boldsymbol{Q}_1$ and $\boldsymbol{Q}_1$ respectively, and the relative attitude $\delta\boldsymbol{Q}$ is

$$\delta\boldsymbol{Q} = \begin{bmatrix} \delta\eta \\ \delta\boldsymbol{q} \end{bmatrix} = \begin{bmatrix} \eta_1\eta_2 + \boldsymbol{q}_1^T \boldsymbol{q}_2 \\ \eta_1\boldsymbol{q}_2 - \eta_1\boldsymbol{q}_2 - \tilde{\boldsymbol{q}}_1\boldsymbol{q}_2 \end{bmatrix} \tag{10}$$

When the two coordinate systems point to the same point, then $\delta\eta = 1$, $\delta\boldsymbol{q} = 0_3$.

Cartesian Path Planning Problem

Problem description

In this paper, the non-holonomic path planning problem of space robot under jerk constraints is studied. The influence of manipulator motion on the attitude of the base should be considered, and the disturbance of the base should be as small as possible. The operating environment of space robot is different from that of ordinary industrial robot, and its service life is an important consideration. An important factor affecting the service life of space robot is the jerk of joints, which will not only affect its service life, but

also affect its accuracy. To solve the above problems, a path planning model of space robot considering jerk constraints is proposed in this paper. By controlling the motion of the manipulator joints, the joint angle and the base attitude angle of the manipulator are converging to the desired state at the same time, so as to ensure the relocation of the base attitude of the space robot during the motion process.

For the convenience of discussion and research, the hypothetical conditions for the study of space robot in this paper are as follows:

1) All components of the space robot system are rigid bodies, and each connecting rod joint has a rotational degree of freedom;
2) The movement of space robot solar panels and the shaking of fuel are not taken into account;
3) Ignoring the influence of microgravity, various friction and resistance, the space robot system is not affected by any external force and torque, and linear momentum and angular momentum are conserved.
4) The effect of orbital mechanics on the trajectory of space robot is ignored.

Parameterization of the trajectory

Because the sine function has the property of boundary, this paper uses the seventh order polynomial sine function to describe the joint trajectory motion of the space robot. At this time, the displacement, velocity, acceleration and jerk of each joint are continuous, and the motion mutation is avoided.

$$\theta_i(t) = \Delta_{i1} sin\left(\sum_{j=0}^{7} \alpha_{ij} t^j\right) + \Delta_{i2} \tag{11}$$

Where $\Delta_{i1} = \dfrac{\theta_{i\_\max} - \theta_{i\_\min}}{2}$, $\Delta_{i2} = \dfrac{\theta_{i\_\max} + \theta_{i\_\min}}{2}$。

The joint velocity is

$$\dot{\theta}_i(t) = \Delta_{i1} cos\left(\sum_{j=0}^{7} \alpha_{ij} t^j\right)\left(\sum_{j=0}^{6} (j+1)\alpha_{i(j+1)} t^j\right) \tag{12}$$

The joint acceleration function is

$$\ddot{\theta}_i(t) = -\Delta_{i1} sin\left(\sum_{j=0}^{7} \alpha_{ij} t^j\right)\left(\sum_{j=0}^{6} (j+1)\alpha_{i(j+1)} t^j\right) + \Delta_{i1} cos\left(\sum_{j=0}^{7} \alpha_{ij} t^j\right)\left(\sum_{j=0}^{5} (j+2)(j+1)\alpha_{i(j+2)} t^j\right) \tag{13}$$

The secondary acceleration function of the joint is

$$\begin{aligned}\dddot{\theta}_i(t) = & -\Delta_{i1} cos\left(\sum_{j=0}^{7} \alpha_{ij} t^j\right)\left(\left(\sum_{j=0}^{6} (j+1)\alpha_{i(j+1)} t^j\right)\right)^3 \\ & -2\Delta_{i1} sin\left(\sum_{j=0}^{7} \alpha_{ij} t^j\right)\left(\sum_{j=0}^{6} (j+1)\alpha_{i(j+1)} t^j\right)\left(\sum_{j=0}^{5} (j+2)(j+1)\alpha_{i(j+2)} t^j\right) \\ & -\Delta_{i1} sin\left(\sum_{j=0}^{7} \alpha_{ij} t^j\right)\left(\sum_{j=0}^{6} (j+1)\alpha_{i(j+1)} t^j\right)\left(\sum_{j=0}^{5} (j+2)(j+1)\alpha_{i(j+2)} t^j\right) \\ & +\Delta_{i1} cos\left(\sum_{j=0}^{7} \alpha_{ij} t^j\right)\left(\sum_{j=0}^{4} (j+3)(j+2)(j+1)\alpha_{i(j+3)} t^j\right)\end{aligned} \tag{14}$$

Constraint conditions

During the motion of the space robot, the angle, velocity and acceleration of each joint are all subject to certain physical limitations. At the initial and final moments, the velocity and acceleration of each joint are all zero. This paper considers the addition of secondary acceleration constraints to ensure that the jerk

is within a safe range, which is beneficial to improve the service life of the joints. The space robot satisfies the following equality constraints and inequality constraints during the planning process.

Equality constraints:

$$\begin{aligned}&\theta_i(t_0)=\theta_{i0},\dot{\theta}_i(t_0)=0,\ \ddot{\theta}_i(t_0)=0\\&\theta_i(t_f)=\theta_{if},\dot{\theta}_i(t_f)=0,\ \ddot{\theta}_i(t_f)=0\end{aligned} \tag{15}$$

Inequality constraints:

$$\begin{aligned}&\theta_{i\_\min}\le\theta_i(t)\le\theta_{i\_\max}\\&\dot{\theta}_{i\_\min}\le\dot{\theta}_i(t)\le\dot{\theta}_{i\_\max}\\&\ddot{\theta}_{i\_\min}\le\ddot{\theta}_i(t)\le\ddot{\theta}_{i\_\max}\end{aligned} \tag{16}$$

In order to ensure that the space robot can work smoothly and the jerk is within a safe range, the constraint on joint jerk is added in this paper, namely

$$\left\|\dddot{\theta}_i(t)\right\|\le\bar{J}_i \tag{17}$$

Among them, $\bar{J}_i$ is the upper limit of the jerk of the joint *i* respectively.

Objective function

The goal of space robot trajectory planning is to generate the applicable joint motion law without violating the constraint conditions, so that the joint angle and the attitude of the base of space robot can reach the desired state at the same time, so as to complete the desired space task. In this paper, the cost function of the base disturbance is defined as

$$\min f_1(t)=\left\|\delta q_b\right\| \tag{18}$$

Since the total external force and the total external moment of the space robot system are 0, the position and attitude of the base at the final moment is shown in equation (19)

$$q_b^f=q_b^s+\int_{t_s}^{t_f}\frac{1}{2}\begin{bmatrix}-\boldsymbol{q}_b\\ \eta_b\boldsymbol{1}-\tilde{\boldsymbol{q}}_b\end{bmatrix}J_{bm\_w}\dot{\theta}\,dt \tag{19}$$

The error between the final attitude and the desired attitude of the space robot base is

$$\delta\boldsymbol{q}_b=\eta_b^d\boldsymbol{q}_b^f-\eta_b^f\boldsymbol{q}_b^d-\boldsymbol{q}_b^{\square f}\boldsymbol{q}_b^d \tag{20}$$

In order to ensure the working efficiency of space robot, the cost function of time is defined as

$$\min f_2(t)=t_f \tag{21}$$

In order to make the space robot meet the requirements of work efficiency and base stability, the total operating time and base disturbance are used as components to establish a comprehensive and optimal objective function of time and base disturbance.

$$\min f(t)=K_b f_1(t)+K_t f_2(t) \tag{22}$$

Where K_b is the weight of the base disturbance, and K_t is the weight of time, $K_T+K_b=1$.

Solution of the Path Planning Problem based on PSO

Particle Swarm Optimization Algorithm

Particle Swarm Optimization (PSO) [28-30] is an intelligent optimization algorithm based on random search, which has high efficiency and effectiveness. The key to particle swarm optimization is to determine the local and global optimal values of particles, and make use of information sharing by individuals in the group to make the whole group movement in problem solving space from disorder to order evolution process. The particle uses its own experience and the best experience in the group to update the next movement, so as to obtain the optimal solution to the problem.

The particle updates its velocity and position according to the following formula:

$$\begin{aligned} v_{ij}(t+1) &= \omega \cdot v_{ij}(t) + c_1 r_1 \left(pBest_{ij}(t) - x_{ij}(t) \right) + c_1 r_1 \left(gBest_j(t) - x_{ij}(t) \right) \\ x_{ij}(t+1) &= x_{ij}(t) + \delta \cdot v_{ij}(t+1) \end{aligned} \tag{23}$$

Among them, $pBest_{ij}(t)$ is the optimal solution known to the individual, $gBest(t)$ is the optimal solution known to the population, ω is the inertia weight, c_1, c_2 are the learning factor, r_1, r_2 are the random number within [0,1], and δ is the velocity adjustment factor.

Non-holonomic path planning based on PSO

The advantage of particle swarm optimization lies in its method based on swarm intelligence and its fast convergence velocity. By using the 7th-order polynomial sine function to parameterize the joint angle, and substituting the equation constraint condition (15) into the formulas (11)-(13), we can get

$$\begin{aligned} \alpha_{i0} &= \arcsin\left(\frac{\theta_{i0} - \Delta_{i2}}{\Delta_{i1}}\right), \ \alpha_{i1} = 0, \ \alpha_{i2} = 0 \\ \alpha_{i3} &= \frac{10\left(\arcsin\left(\frac{\theta_{if} - \Delta_{i2}}{\Delta_{i1}}\right) - \arcsin\left(\frac{\theta_{i0} - \Delta_{i2}}{\Delta_{i1}}\right)\right) - \left(3\alpha_{i7}t^7 + \alpha_{i6}t^6\right)}{t^3} \\ \alpha_{i4} &= \frac{-15\left(\arcsin\left(\frac{\theta_{if} - \Delta_{i2}}{\Delta_{i1}}\right) - \arcsin\left(\frac{\theta_{i0} - \Delta_{i2}}{\Delta_{i1}}\right)\right) + 8\alpha_{i7}t^7 + 3\alpha_{i6}t^6}{t^4} \\ \alpha_{i5} &= \frac{6\left(\arcsin\left(\frac{\theta_{if} - \Delta_{i2}}{\Delta_{i1}}\right) - \arcsin\left(\frac{\theta_{i0} - \Delta_{i2}}{\Delta_{i1}}\right)\right) - \left(6\alpha_{i7}t^7 + 3\alpha_{i6}t^6\right)}{t^5} \end{aligned} \tag{24}$$

Therefore, each joint of the space robot contains two parameters α_{i6} and α_{i7}.

The fitness function is the optimization index of the algorithm. Different optimization goals have different evaluation indexes. In the process of trajectory planning of space robot, it is necessary to ensure that the velocity, acceleration and secondary acceleration of the joint are within the specified range, so the penalty function mechanism is introduced to ensure that.

$$J = K_b \frac{\|\delta q_b\|}{k_q} + K_t t_f + \frac{F_{\dot\theta}}{k_{\dot\theta}} + \frac{F_{\ddot\theta}}{k_{\ddot\theta}} + \frac{F_{\dddot\theta}}{k_{\dddot\theta}} \tag{25}$$

Among them, K_b is the weight of the base disturbance, K_t is the weight of time, $F_{\dot\theta}$, $F_{\ddot\theta}$ and $F_{\dddot\theta}$ are determined according to the joint angular velocity, angular acceleration and angular secondary acceleration, As formulas (26)-(28), $k_{\dot\theta}$, $k_{\ddot\theta}$, $k_{\dddot\theta}$ are the corresponding penalty factors respectively.

$$F_{\dot\theta} = \max_{i\in[1:6]}\left(F_{\dot\theta_i}\right) = \begin{cases} 0 & if\ \dot\theta_{i\_max} \le \dot\theta_{i\_limit} \\ \dfrac{\dot\theta_{i\_max} - \dot\theta_{i\_limit}}{\dot\theta_{i\_limit}} & else \end{cases} \tag{26}$$

$$F_{\ddot\theta} = \max_{i\in[1:6]}\left(F_{\ddot\theta_i}\right) = \begin{cases} 0 & if\ \ddot\theta_{i\_max} \le \ddot\theta_{i\_limit} \\ \dfrac{\ddot\theta_{i\_max} - \ddot\theta_{i\_limit}}{\ddot\theta_{i\_limit}} & else \end{cases} \tag{27}$$

$$F_{\dddot\theta} = \max_{i\in[1:6]}\left(F_{\dddot\theta_i}\right) = \begin{cases} 0 & if\ \dddot\theta_{i\_max} \le \dddot\theta_{i\_limit} \\ \dfrac{\dddot\theta_{i\_max} - \dddot\theta_{i\_limit}}{\dddot\theta_{i\_limit}} & else \end{cases} \tag{28}$$

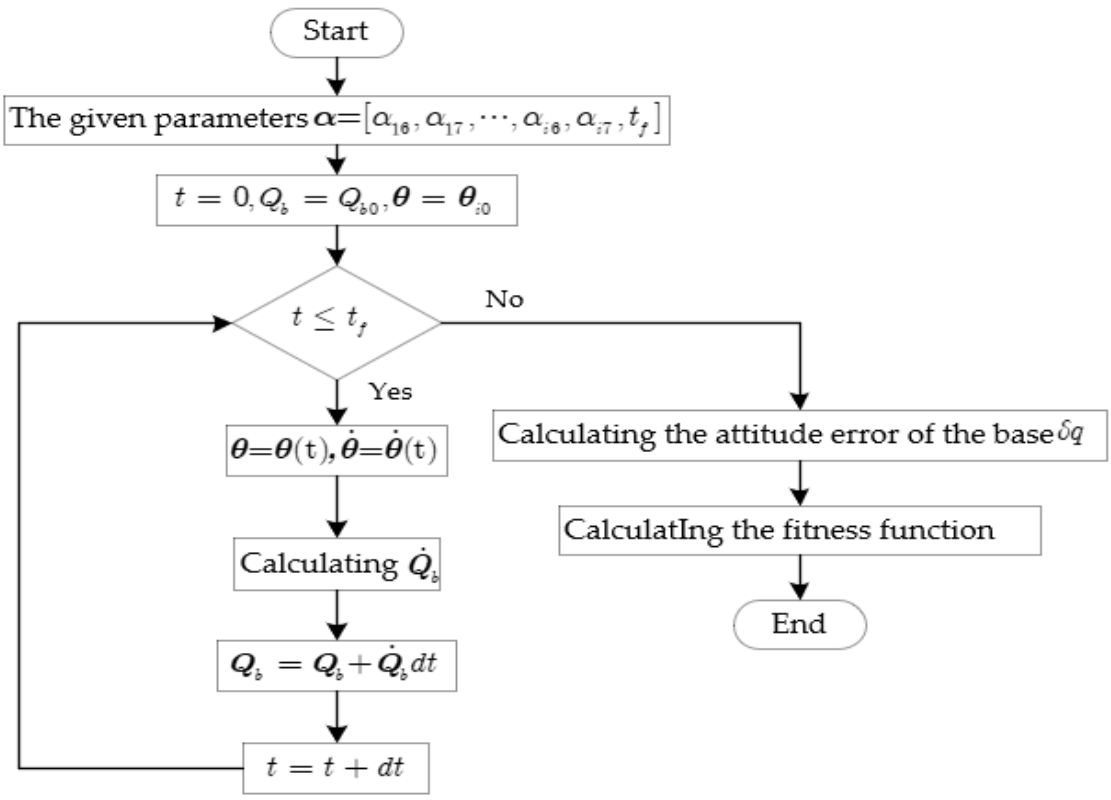

Figure 2: The calculation flow chart of fitness function.

The calculation flow chart of fitness function is shown in Figure 2.

In this paper, particle swarm optimization algorithm is used to solve the path planning model based on the jerk constraints to find the best parameter $\alpha=\left[\alpha_{16},\alpha_{27},...,\alpha_{i6},\alpha_{i7},t_f\right]$ the particle swarm optimization algorithm is used to solve the non-holonomic path planning based on jerk constraint.

Simulation Research

In order to solve the problem of minimum perturbation of the base and optimal time of the space robot, this paper uses the 7th-order sinusoidal polynomial function to parameterize the joint angle. According to the objective function and constraint conditions, the fitness function of the algorithm was defined, the practical problem was transformed into an optimization problem, and the optimal path of the space robot was determined by finding the minimum value of the fitness function.

Basic parameters of space robot

The space robot system studied in this paper is composed of a base and a 6-DOF manipulator. The DH system of the space robot is shown in Figure 3, the DH parameters are shown in Table 1, and the dynamic parameters are shown in Table 2.

According to the task requirements of the space robot, the non-holonomic path trajectory is planned in the given initial state and target state, and the planned trajectory function is required to be continuous and smooth to make the space robot manipulator move smoothly.

Experimental results

The joint angle at the initial moment of the space robot is set as $\theta_{i0}=\left[10°,30°,45°,-20°,-25°,40°\right]$ and the desired joint angle at the final moment is set as $\theta_{id}=\left[40°,60°,90°,-10°,-30°,60°\right]$ the Euler angle of the base at the initial moment is expressed as $\psi_{b0}=\left[6°,15°,7°\right]^T$, and the expected Euler angle

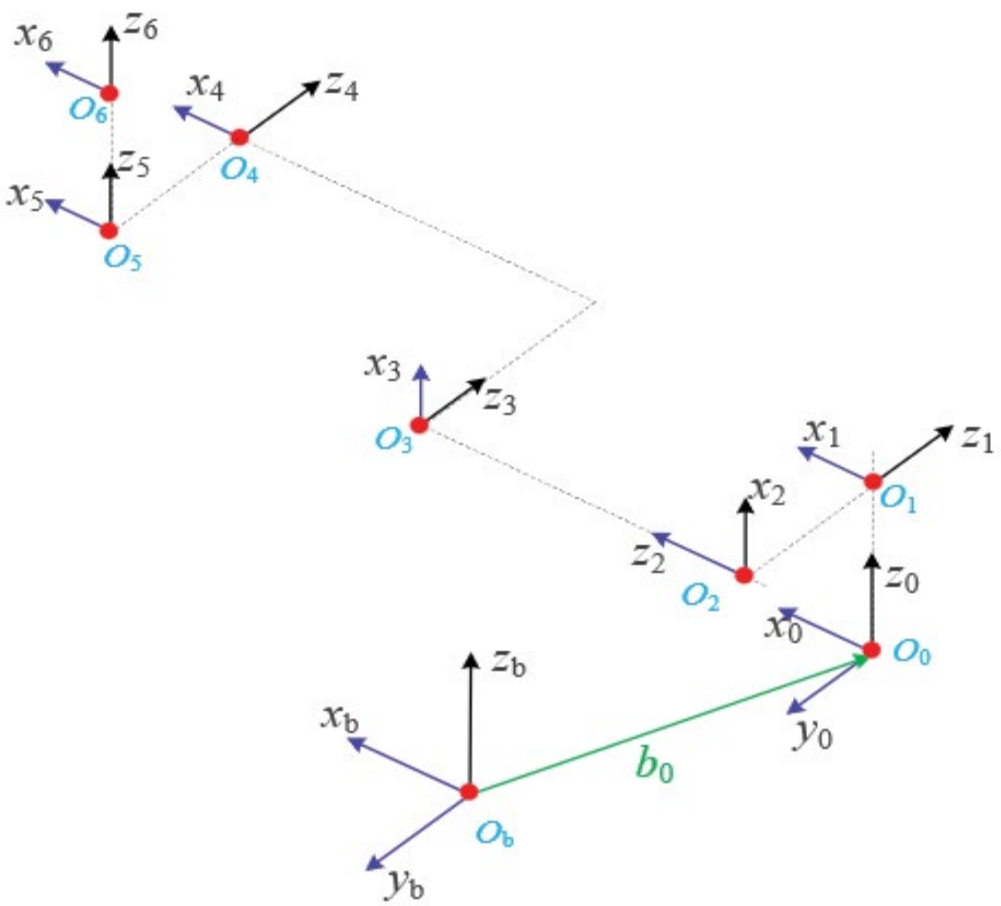

Figure 3: The DH system of the space robot.

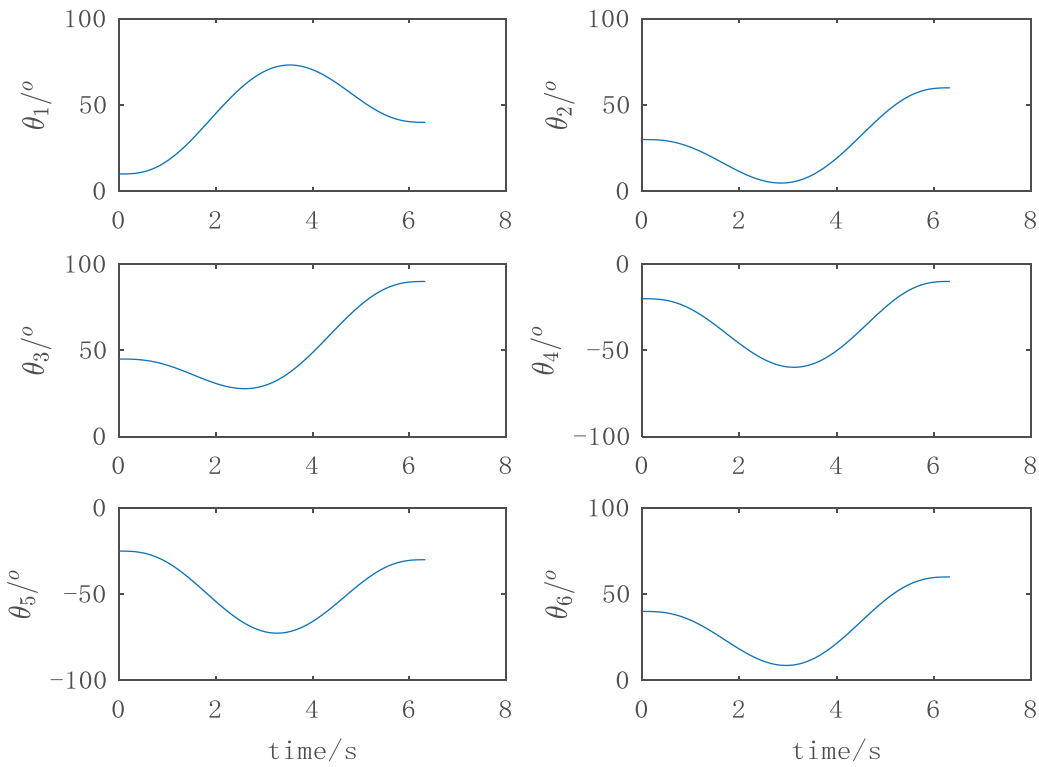

Figure 4: The trajectory curve of each joint of space robot.

Table 1: The DH parameters of the space robot.

No.	a_l/mm	d_l/mm	$\alpha_l/\deg$	$\phi_l/\deg$
1	0	115	90	0
2	0	-115	90	90
3	0	775	-90	0
4	875	240	0	-90
5	0	-115	90	0
6	0	115	0	0

Table 2: The dynamic parameters of the space robot.

		Base	Link 1	Link 2	Link 3	Link 4	Link 5	Link 6
m/kg		600	6.3	6.9	8.9	11	4.7	4.9
${}^iI_i/kg.m^2$	I_{xx}	75	0.004	0.004	0.46	0.95	0.003	0.02
	I_{yy}	74	0.006	0.006	0.47	0.94	0.005	0.02
	I_{zz}	74	0.004	0.008	0.01	0.008	0.003	0.015
	I_{xy}	0.25	0	-0.001	0	0	0	0
	I_{xz}	0.32	0	0	0	0	0	0
	I_{yz}	0.19	0	0	-0.03	-0.02	0	0
${}^ia_i/m$			0	0.03	0	0	0	0
			0	0	0.01	-0.425	0.01	0
			0.065	-0.055	0.325	0.13	-0.05	0.04
${}^ib_i/m$		-0.35	0	-0.03	0	0	0	0
		-0.35	0	0	-0.01	-0.45	-0.01	0
		0.4	0.05	-0.06	0.45	0.11	-0.065	0.075

of the base at the final moment is set as $\psi_{bd} = [0°, 0°, 0°]^T$. The range of joint angle of space robot is shown as follows:

$$\begin{aligned} &-165 \le \theta_1 \le 165,\ -130 \le \theta_2 \le 250 \\ &-140 \le \theta_3 \le 160,\ -170 \le \theta_4 \le 170 \\ &-300 \le \theta_5 \le 300,\ -150 \le \theta_6 \le 150 \end{aligned} \tag{29}$$

The range of joint angular velocity is shown in the following formula:

$$\left|\dot{\theta}_i(t)\right| \le 60\deg/s,\ i = 1,\ldots,6 \tag{30}$$

The range of joint angular acceleration is shown in the following formula:

$$\left|\ddot{\theta}_i(t)\right| \le 70\deg/s^2,\ i = 1,\ldots,6 \tag{31}$$

The range of joint angle secondary acceleration is shown in the following formula:

$$\left|\dddot{\theta}_i(t)\right| \le 80\deg/s^3,\ i = 1,\ldots,6 \tag{32}$$

The coefficient of the fitness function is determined by the accuracy requirement. In this article, we assume that the rotation angle of the base attitude does not exceed 1_{deg}. Therefore, the coefficients of fitness function should be defined separately, as shown in the following formula:

$$k_q = sin\left(\frac{\phi}{2} \times \frac{}{180}\right),\ k_{\dot{\theta}} = 0.01,\ k_{\ddot{\theta}} = 0.01,\ k_{\dddot{\theta}} = 0.01,\ K_b = 0.9,\ K_t = 0.1 \tag{33}$$

The particle swarm optimization algorithm is very sensitive to parameters, and the corresponding parameters in this experiment are set as: The number of iterations is N_{max} = 1000, the population size is NP = 150, the maximum inertia weight is w_{max} = 0.9, the minimum inertia weight is w_{min} = 0.1, the accelerated constant is $c_1 = c_2 = 2$.

Through simulation calculation, the optimal parameters searched by the particle swarm optimization algorithm is

$$\alpha = \left[-3.8208, 1.7764, -2.0585, 3.2927, 5.2949, 9.9397, -1.1520, 0.8619, 1.2449, 1.0670, 0.4441, 0.8062, 6.3304\times10^{5}\right]\times10^{-5}$$

The minimum value of fitness function is $J^* = 3.223$.

It can be seen from Figure 4 that during the entire movement, the joint angles are within the range of the manipulator joint angle. From Figure 5, it can be seen that the joint angular velocity, joint angular acceleration, and joint angular secondary acceleration also meet the corresponding constraints. In order to display the change of the base attitude intuitively, ZYX Euler angle is adopted in this paper to represent the base attitude. As can be seen from Figure 6, the base attitude is adjusted to the desired attitude. The simulation results show that the problem of low maintenance efficiency and high base disturbance of space robot can be effectively solved by using particle swarm optimization algorithm to solve the problem of base disturbance based on jerk constraint and time comprehensive optimal path planning.

Conclusion

According to the operation requirements of on-orbit maintenance tasks, space robot needs to adjust its attitude when completing some on-orbit operation tasks. There is a dynamic coupling relationship between the base of space robot system and the manipulator, and the attitude of the base can be adjusted by the motion of the joints. This paper uses the non-holonomic characteristics of the space robot to achieve the desired value of the joint angle and the attitude of the base at the same time, and a comprehensive model of optimal path planning is established for base disturbance and time based on the jerk constraint by using the 7th-order polynomial sine function to parameterize the joint angle, and the path planning model is used to plan the path of the space robot, so that the velocity, acceleration, and

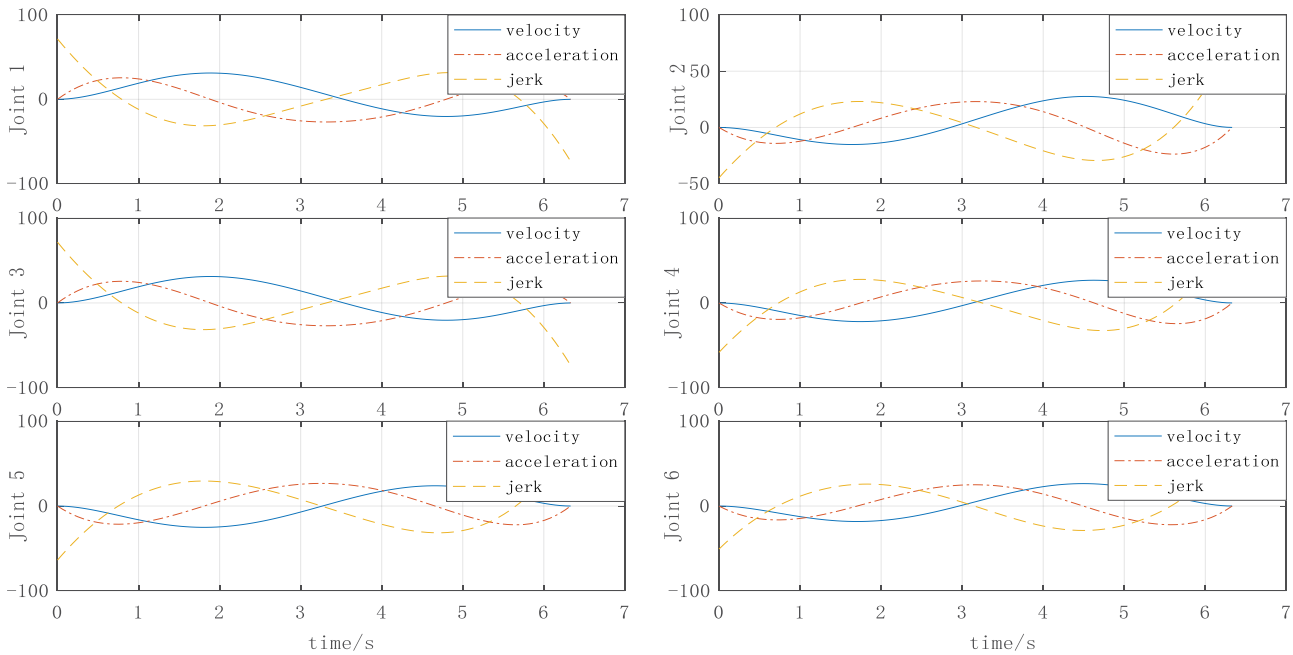

Figure 5: Curves of angular velocity, acceleration and secondary acceleration of each joint of space robot.

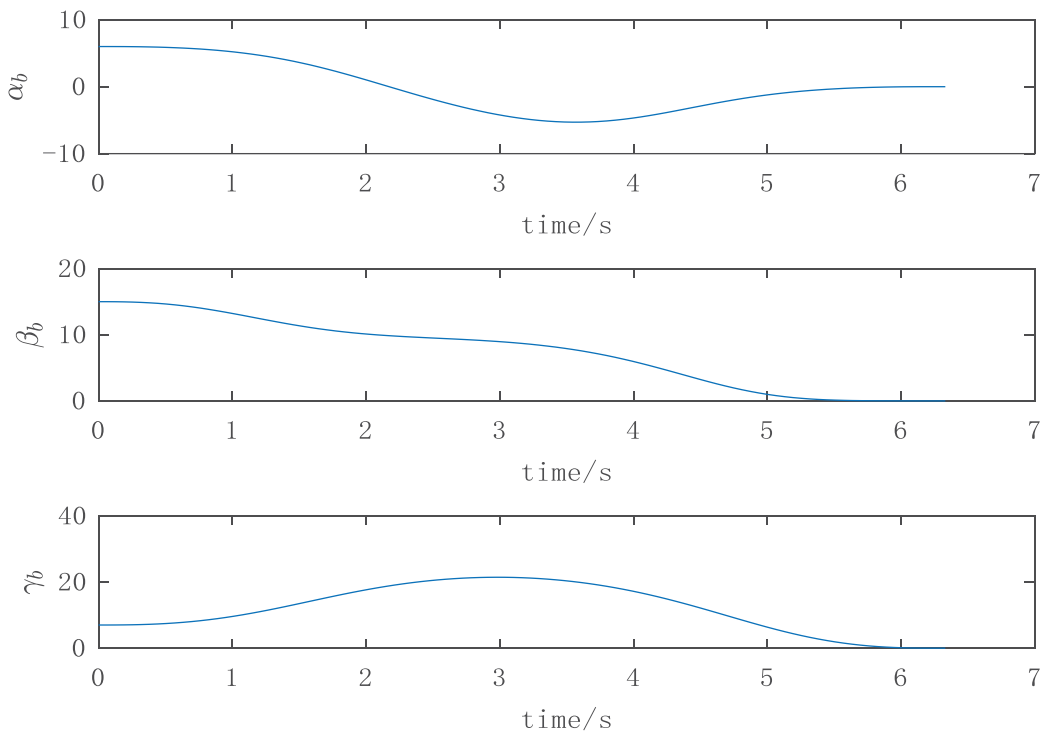

Figure 6: The attitude change curve of the space robot base.

secondary acceleration of each joint of the space robot meet the kinematic constraints. The simulation results show that the non-holonomic path planning based on jerk constraints can solve the problems of low efficiency and large base disturbance of 15 space robot in orbit maintenance more effectively.

Acknowledgments

This study is supported by the Natural Science Foundation of Shandong Province (No. ZR2022QE199) and the Open Project Program of Shandong Marine Aerospace Equipment Technological Innovation Center, Ludong University (No. MAETIC202207).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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