Research on Vibration Suppression for Space Manipulator Based on PSO Algorithm

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Abstract

A space manipulator undertakes tasks of cabin translocation, transfer, and installation of equipment, as well as serves as an astronaut auxiliary in a station system. However, the greatest disadvantage of the space manipulator is the vibration problem due to the flexibility of joint and link. The residual vibration significantly reduces the end-point accuracy of the manipulator [1]. Therefore, the best scheme is in which the flexible manipulator completes the required move with minimal residual vibration.

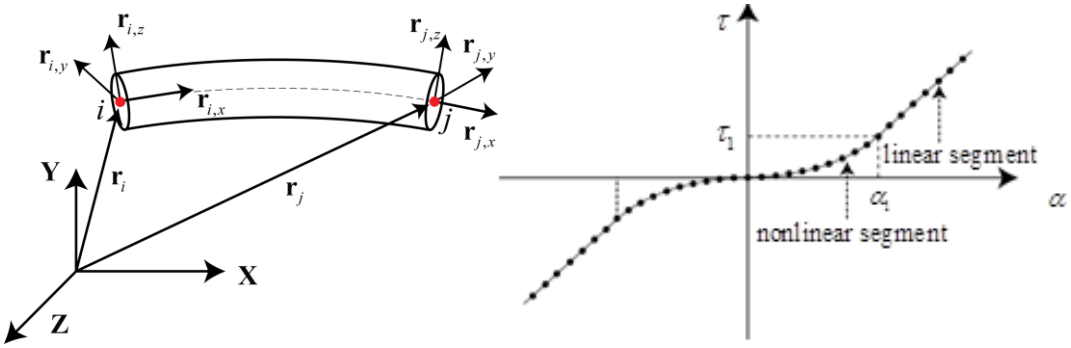


Figure 1: ANCF beam element and nonlinear torque-angle curve.

With absolute nodal coordinate formulation (ANCF), large deformation and rotation can be described accurately. Three-dimensional beam element with two nodes [2] is used to model flexible space manipulator links and nonlinear torque–angle relationship to model flexible joint. Dynamic equations for this multibody system can be typically express as (1) a set of DAEs that combine differential and algebraic equations which are solved by generalized-α algorithm [3].

$$\begin{cases} \mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}_{\mathbf{q}}^{\mathrm{T}}\boldsymbol{\lambda} = \mathbf{Q}(\mathbf{q}) - \mathbf{F}(\mathbf{q}) \\ \mathbf{C}(\mathbf{q},t) = \mathbf{0} \end{cases} \tag{1}$$

To reduce the residual vibration, a new cosine-based function as (2) is proposed to plan the joint trajectory. Figure 2 shows that the proposed method has a better optimization performance than regular fifth-polynomial function and cycloidal motion function with a one-link space manipulator whose link length is $3.5m$.

$$\tilde{\theta}(t) = (\theta_f - \theta_0)[a_0 + a_1\cos(\frac{\pi t}{t_f}) + a_3\cos(\frac{3\pi t}{t_f})] + \theta_0 \tag{2}$$

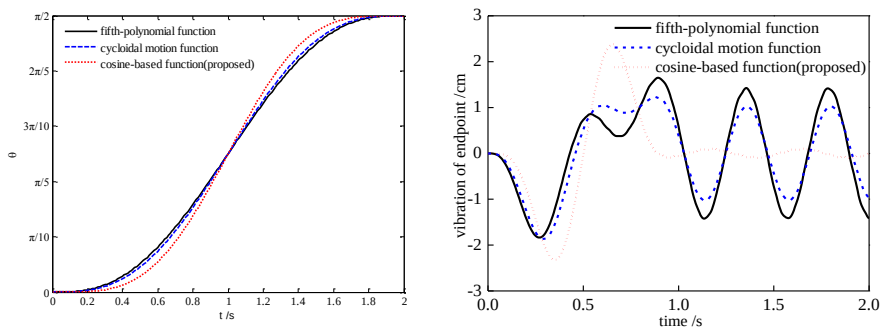


Figure 2: Schematic diagram of trajectory planning.(a) trajectory planning functions;(b)residual vibration of three functions;

Suppose trajectory is set in Cartesian space, inverse kinematics needs to be used to transfer the trajectory into joint movements in joint space, which is described as follows:

$$\begin{cases} \dot{\boldsymbol{\theta}} = \mathbf{J}^{+}\dot{\mathbf{X}} + (\mathbf{I} - \mathbf{J}^{+}\mathbf{J})\mathbf{e}_1 \\ \ddot{\boldsymbol{\theta}} = \mathbf{J}^{+}(\ddot{\mathbf{X}} - \dot{\mathbf{J}}\dot{\boldsymbol{\theta}}) + (\mathbf{I} - \mathbf{J}^{+}\mathbf{J})\mathbf{e}_2 \end{cases} \tag{3}$$

where $\mathbf{J}^{+}$ is the pseudo-inverse matrix of $\mathbf{J}$, $\mathbf{J}^{+} = \mathbf{J}^{\mathrm{T}}(\mathbf{J}\mathbf{J}^{\mathrm{T}})^{-1}$; $\mathbf{I}$ is unit matrix; $\mathbf{e}_1, \mathbf{e}_2 \in R^n$ are random vectors which named coefficients of movement.

Also the constriction factor Particle Swarm Optimization(PSO) algorithm proposed by Clerc helps to optimize coefficients of movement $\mathbf{e}_1$ and $\mathbf{e}_2$ respectively, to reduce the residual vibration of the endpoint of flexible links. Velocities and positions of particles change as follows:

$$\begin{cases} \boldsymbol{v}_i^{(t+1)} = \chi[\boldsymbol{v}_i^{(t)} + c_1 r_1(\boldsymbol{pbest}_i^{(t)} - \boldsymbol{x}_i^{(t)}) \\ \qquad\qquad + c_2 r_2(\boldsymbol{gbest}^{(t)} - \boldsymbol{x}_i^{(t)})] \\ \boldsymbol{x}_i^{(t+1)} = \boldsymbol{x}_i^{(t)} + \boldsymbol{v}_i^{(t+1)} \end{cases} \tag{4}$$

where $\boldsymbol{pbest}_i$ is the best position of particle i; $\boldsymbol{gbest}$ is the best position of all particles; χ is the constriction factor.

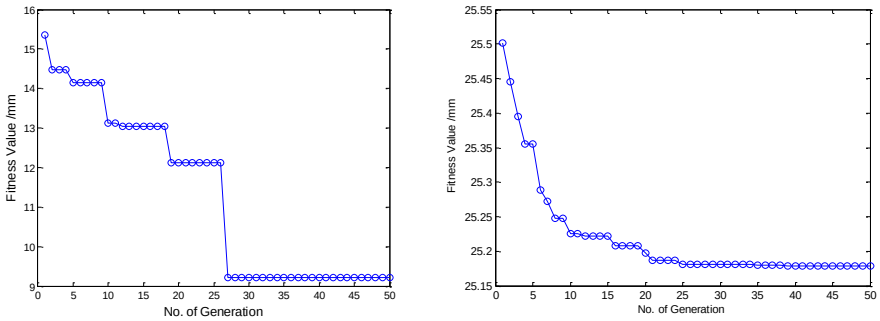
Two simulation examples are completed to validate the proposed optimization process. The track of endpoints is a straight line which will be transferred to joint space by inverse kinematics with a three-link manipulator whose every link length is $1m$.

Case 1: Optimization in the level of angular velocity.

Set $\mathbf{e}_2 = \mathbf{0}$ and only optimize $\mathbf{e}_1$. The population size is 50 and maximum generation is 50.

Case 2: Optimization in the level of angular acceleration.

Optimize $\mathbf{e}_2$ and calculate $\mathbf{e}_1$ by Runge-kutta method. The population size is 50 and maximum generation is 50.



(a) (b)

Figure 3: Amplitudes of residual vibration.(a)optimizing $\mathbf{e}_1$;(b)optimizing $\mathbf{e}_2$;

Results show that optimizing $\mathbf{e}_2$ does not achieve much comparing with optimizing $\mathbf{e}_1$, which suggests that we should concentrate on the level of angular velocity. And with proposed cosine-based trajectory function and PSO algorithm, the residual vibration can be supressed within $10mm$, which is far better performance than that of other regular functions. Notably, the effectiveness of the proposed method in weakening the residual vibration is only verified by numerical simulations and only optimizing $\mathbf{e}_1$ is effective.

References

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[3] Arnold M, Brüls O. Convergence of the generalized-a scheme for constrained mechanical systems. Multibody System Dynamics, Vol. 18, No. 2, pp. 185-202, 2007.