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# Study on Vibration of Heavy-Precision Robot Cantilever Based on Time-varying Glowworm Swarm Optimization Algorithm

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**Abstract.**A method of terminal vibration analysis based on Time-varying Glowworm Swarm Optimization algorithm is proposed in order to solve the problem that terminal vibration of the large flexible robot cantilever under heavy load precision.The robot cantilever of the ballastless track is used as the research target and the natural parameters of the flexible cantilever such as the natural frequency, the load impact and the axial deformation is considered. Taking into account the change of the minimum distance between the glowworm individuals, the terminal vibration response and adaptability could meet. According to the Boltzmann selection mechanism, the dynamic parameters in the motion simulation process are determined, while the influence of the natural frequency and the load impact as well as the axial deformation on the terminal vibration is studied. The method is effective and stable, which is of great theoretical basis for the study of vibration control of flexible cantilever terminal.

## 1. Introduction

The design and control of flexible manipulator are widely studied and applied in the fields of robotics and aerospace technology. The traditional robots can guarantee the high speed and high precision performance with the rigid manipulator, while the solution of the arm inverse will increase the computational complexity and reduce the accuracy of the robot with the increase of the number of joints. In particular, due to the heavy load conditions, its long arm and bearing large, the robot cantilever prone to deformation in the process of rotation or amplitude, such as track robot cantilever components. Therefore, a new optimization algorithm is needed to solve the high-precision inverse of the redundant robot arm. As a new intelligent algorithms, the Glowworm Swarm Optimization (GSO) algorithm has been successfully applied to various engineering fields and multi-modal function optimization.

Song[1] Considered the dynamic modeling and simulation of flexible manipulator in complex load conditions. Leung et al[2] focused on the analysis of nonlinear dynamic multi-body flexible systems. Yang et al[3] on the hydraulic excavator mechanical cantilever for the determination of the natural frequency and sensitivity calibration. Xu et al[4] simulated the natural frequency of the crane boom and analyzed the frequency change. Viktorova et al[5] explored the causes of hand-arm vibration and frequency response analysis. Sayahkarajy et al[6] proposed a two-link flexible manipulator control method for mixed vibration and no-load heavy loads. The above content in the robot dynamics modeling, trajectory planning and control made a lot of research results. However, the nonlinear dynamic effects of rigid and the effect of flexible deformation of the whole system in the space-time field are neglected. In addition, Wang et al[7] use the GSO algorithm to optimize the BP neural network initial weight and threshold. Yu et al[8] used the randomness of chaos system to initialize GSO to improve the algorithm's global search ability. Gong et al[9] solve the multi-dimensional problem effectively based on hybrid artificial GSO algorithm. Wu et al[10] improve the artificial bee colony algorithm and particle swarm optimization algorithm, and through experiments to verify the GSO algorithm is better. Shen et al[11] proposed a new multi-objective optimization genetic algorithm to optimize the robot joint angle. At present, there is no scholar using GSO algorithm and robot arm inverse into combination.

In this paper, a new method based on Glowworm Swarm Optimization of Time-varying（TVGSO） is proposed to solve the vibration characteristics of robot cantilever under heavy load precision condition, which is due to automatic control, deformation of bar, joint vibration and inertial mass. Based on the golden ratio segmentation theory, the Boltzmann selection mechanism is used to analyze the time-varying step, while the time-varying process is based on the minimum distance between the glowworm and the individual glowworm choose the direction and position in the search process. Finally, compared with the original GSO algorithm, the accuracy and stability of the TVGSO algorithm are better, which is of great theoretical basis for the study of the vibration control of the flexible cantilever terminal.

## 2. Dynamic model of heavy-precision cantilever for flexible robot

### *2.1 Establishment of Cantilever Generalized Coordinate System for Flexible Robot*

Cantilever model of ballastless tracked robot as shown in Figure 1; the Euler-Bernoulli beam model with simplified flexible cantilever as shown in Figure 2. The basic parameters of the cantilever are as follows: concentrated mass $M_0$, unit length mass $m$, initial length L, flexibility $\delta$, in addition, $H_0$, $H_1$ for the hydraulic drive cylinder position. XOY is the inertia coordinate, and the angle θ between the coordinate axes $O_{X1}$ and $O_X$ is a rigid angle. Hydraulic flexible mechanical arm shows worse accuracy and stability, due to servo hydraulic cylinder vibration, hydraulic cylinder and the arm joint card and mechanical arm rod elastic vibration and other factors, while affecting its dynamic characteristics and control characteristics.

### *2.2 Modeling of Flexible Manipulator Dynamics Equation*

According to the theory of dynamic manipulator of flexible manipulator, the dynamic equation is established[12]. The kinetic equation of the flexible arm is obtained by the hypothetical modal method. As shown in Figure 2, the flexural displacement of the flexible arm is set according to $w(l,t)$ in the ideal state. The length of the hydraulic cylinder l, the actual output force F:

**Figure 1**. Cantilever model of ballastless tracked robot

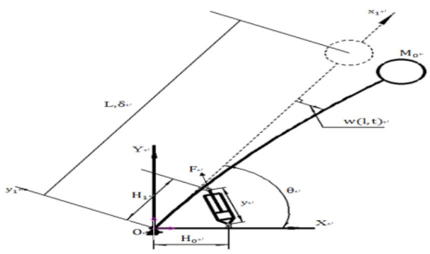


**Figure 2.** the Euler-Bernoulli beam model with simplified flexible cantilever

$$w(l,t) = \sum_{i-1}^{n} \Phi_i(l) q_i(t) \tag{1}$$

Where $\Phi_i(l)$ denotes the modal function of the hinge-free end model, $q_i(t)$ denotes the generalized modal coordinates of the articulated-free end model, and n is the modal order. The kinetic energy and potential energy of the flexible arm system are denoted by C and G respectively, and the potential energy G is the sum of the potential energy potential and the elastic potential energy. The kinetic equation of the flexible manipulator is based on the Lagrangian equation as follows:

$$H(q)\ddot{q} = C(q,\breve{q})\breve{q} + G(q) = \tau \tag{2}$$

$h_{ij} = \left( \frac{\partial^0 A_k}{\partial p_i} J_k \frac{\partial ({}^0 A_k)^T}{\partial p_j} \right)$ is the inertial force $h_{ij}$ proportional to the generalized acceleration; $H(q)\ddot{q}$ is the quadratic form of the generalized velocity, where the term containing $\dot{q}_i^2$ is the centrifugal force and the term of $\dot{q}_i \dot{q}_j (i \neq j)$ ;G (q) is the gravitational term; $\tau$ is the driving force vector of the hydraulic drive system actuator on the flexible manipulator.

According to the equation of the velocity of the flexible manipulator, the elements of the i-th row of the Jacobian matrix J are:

$$J_{ij}(q) = \frac{\partial s_i(q)}{\partial q_i} \tag{3}$$

*2.3 Space-time operator fractal transport equation of flexible robot cantilever*

Ignore the damping C, according to the operator splitting mechanism constraint equation

$$M_f \ddot{q}_f + K_f q_f = Q_f + Q_{vf} \tag{4}$$

$$Q_{vf} = -M_f \ddot{q}_f + \frac{1}{2} \frac{\partial}{\partial q_f} (\dot{q}_f^T M_f \dot{q}_f) \tag{5}$$

Where $Q_{vf}$ is the generalized force elastic component corresponding to the velocity quadratic term; $Q_f$ is the elastic component corresponding to the generalized external force; $M_f$ is the mechanism mass matrix; $K_f$ is the stiffness matrix.

$$M_f = M_f^1 + M_f^2 \tag{6}$$

$$M_f^1 = M_{f1} + M_{f2} \tag{7}$$

$M_f^1$ is the single-order time matrix of the generalized elasticity of the cantilever of the robot; $M_f^2$ is the generalized elastic multilevel time matrix with the end concentrated mass; $M_{f1}$ is the elastic single-order time matrix which does not consider the coupling deformation; $M_{f2}$ Elastic Multi - order Time Matrix Contributing to Coupled Deformation.

The single-order time matrix of the flexible mechanical cantilever system is:

$$M = M_{ff}^1 + M_{ff}^1 = (m + m_1) \begin{bmatrix} \frac{1}{3} & 0 & 0 \\ 0 & \frac{26}{35} & -\frac{221}{210} \\ 0 & -\frac{221}{210} & \frac{21^2}{105} \end{bmatrix} \tag{8}$$

The elastic stiffness matrix of the manipulator can be obtained by the elastic potential of the relative moving coordinate system:

$$U = \frac{1}{2} \int_0^1 [EI(u_{fy}^{''})^2] dx = \frac{1}{2} \int_0^1 [u_{fx}^{'} \cdot u_{fy}^{''}] \begin{bmatrix} EA & 0 \\ 0 & EI \end{bmatrix} \begin{bmatrix} u_{fx}^{'} \\ u_{fy}^{''} \end{bmatrix} dx \tag{9}$$

Where $u_x$ is the lateral displacement of the neutral axis of the manipulator, and $u_y$ is the axial displacement.

*2.4 Optimization of Cantilever Inverse Target for Flexible Robot*

In solving the problem of plane redundant robot arm, if there is no condition constraint, then the solution will be uncertain. First, $\theta^* = [\theta_1^*, \theta_2^*, \cdots, \theta_{N-1}^*]$ satisfy the robot arm solution equation for the target position; Secondly, when the robot arm moves from the initial position to the target position, the joint angle of the robot arm should be as small as possible, that is, to satisfy $f_1(\theta)$ take the minimum value, so the robot arm inverse solution involves multi-objective function optimization.

In this paper, the sum of the absolute values of the difference between the solution value and the theoretical value of the manipulator is less than the given minimum value, and $f_1(\theta)$ is the objective function. The optimal objective function satisfies the redundancy Robot arm inverse solution accuracy. The optimization model as follows:

$$\min f_1(\theta) = (\theta_0 - \theta_0^{ini})^2 + \sum_{k=1}^{N-1} \left[ (\theta_k - \theta_k^{ini}) - \theta_{k-1} - \theta_{k-1}^{ini} \right]^2 \tag{10}$$

## 3. Time-varying glowworm swarm optimization algorithm

*3.1 Basic Glowworm Swarm Optimization Algorithm and Its Defects*

The GSO algorithm has the advantages of low parameters and good stability [8], while its disadvantage of slow convergence and low accuracy of the optimal value affects the overall search performance of the algorithm. The choice of the direction of the glowworm algorithm is in the form of roulette, which leads to the decline of the population diversity, which makes the algorithm prematurely converged and is not conducive to searching the optimal solution.

*3.2 Time-varying step strategy and Boltzmann selection mechanism*

In order to compensate for the shortcomings of the step in the GSO algorithm, the dynamic time-varying step search mechanism is used in the algorithm iteration process. In this paper, the TVGSO algorithm quantifies the minimum distance between the glowworm i and all the glowworm individuals in the field and changes the steps according to the change of the minimum distance. If the minimum distance is less than $s_0$, if the distance is less than $s_0$, if the minimum distance is less than $s_0$, if the minimum distance is less than $s_0$, then take the minimum step size $s_i(t) = 0.618 s_0$.

$$d_{\min} = \min\{\|x_i - x_j\|, j \in N_i(t)\} \tag{11}$$

$$0.618 < \frac{d_{\min}}{s_i(t-1)} < 1, s_i(t) = .0618 s_0 \tag{12}$$

$$0.618^2 < \frac{d_{\min}}{s_i(t-1)} < 0.618, s_i(t) = .0618^2 s_0 \tag{13}$$

Instead of the original roulette way of the glowworm, the Boltzmann selection mechanism dynamically adjusts the direction and position of the search process and the selection pressure during the solution. The probability that the glowworm i moves in the direction of the j-only glowworm in the adjacent area:

$$p_{ij}(t) = \frac{\exp(\frac{l_j(t) - l_i(t)}{T})}{\sum \exp(\frac{l_k(t) - l_i(t)}{T})} T = T_0(\alpha^{t-1}) \tag{14}$$

Where T is the temperature of the simulated annealing algorithm, $T_0$ is the initial temperature of simulated annealing, $\alpha$ is the attenuation factor, and t is the number of TVGSO iterations.

*3.3 Time-varying glowworm swarm optimization algorithm description*

The overall flow of the TVGSO algorithm is described below:

Step 1 Initialize $\rho, \gamma, l_i(0)$ and other constant parameters;

Step 2 Initialize glowworm position randomly, calculate the fitness of each glowworm;

Step 3 The fluorescein value of each glowworm is updated;

Step 4 Enters the motion phase, and the domain set $N_i(t)$ of the glowworm individual i is calculated;

Step 5 Calculate the glowworm i field according to. All glowworm are selected as the probability $p_{ij}(t)$ of the moving object. The minimum distance between glowworm $i$ and glowworm $j$ in the field is calculated. If the distance is less than the initial step, the steps are updated in real time

Step 6 In order to prevent the dynamic decision radius of the glowworm individual from being reduced to 0, the radius of the field of the glowworm i is updated .

Step 7 $t = t + 1$; if there is no iteration to a given number of times, then step 3, otherwise stop the calculation, the output.

## 4. Numerical calculation of cantilever model of flexible robot

**Figure 3** Boltzmann selection mechanism object model

As shown in Figure 3, the Boltzmann selection mechanism model for the glowworm is modeled, and $\omega_1$ corresponds to the $j-th$ transverse bending natural frequency of the rotating cantilever beam[13]. The elastic modulus is $E = 6.875\times10^{10} N/m^2$, the poisson's ratio is $\mu = 0.33$, the shear correction coefficient $k = \frac{10(1+\mu)}{(12+11\mu)} = 0.85$, the length of the beam is $l$, the width is $b$, the density $\rho = 2.767 kg/m^3$, the center rigid body radius $R = 1m$, and the angular velocity $\theta$ is variable.

$$\begin{bmatrix} \omega_1^2 m_{y11} & \cdots & \omega_{Ny}^2 m_{y1Ny} \\ \vdots & \ddots & \vdots \\ \omega_1^2 m_{yNy1} & \cdots & \omega_{Ny}^2 m_{yNyNy} \end{bmatrix} \bullet \begin{bmatrix} \ddot{B}_1 \\ \vdots \\ \ddot{B}_{Ny} \end{bmatrix} = \begin{bmatrix} \dot{\theta}^2 H_{11} - \dot{\theta}^2 m_{y11} + V_{y11} & \cdots & \dot{\theta}^2 H_{1Ny} - \dot{\theta}^2 m_{y1Ny} + V_{y1Ny} \\ \vdots & \ddots & \vdots \\ \dot{\theta}^2 H_{Ny1} - \dot{\theta}^2 m_{yNy1} + V_{yNy1} & \cdots & \dot{\theta}^2 H_{NyNy} - \dot{\theta}^2 m_{yNyNy} + V_{yNyNy} \end{bmatrix} \bullet \begin{bmatrix} \ddot{B}_1 \\ \vdots \\ \ddot{B}_2 \end{bmatrix} \quad (15)$$

The height ratio $\lambda = \alpha / l$ is defined. The variation of the natural frequency p(rad/s) of the first six orders is compared with the different angular velocity $\Omega$. The numerical results are shown in the following Tables 1 and 2.

**Table 1.**Value of basis parameters

| Parameter | $\Omega$ /rad | $l$ /m | $b$ /m | $\lambda$ |
|---|---|---|---|---|
| Value | 5 | 8 | 0.05 | 0.00625 |

**Table 2.**The numerical results of modele

| Order | A | B | C | D |
|---|---|---|---|---|
| 1 | 5.4426 | 6.8738 | 6.8906 | 5.5836 |
| 2 | 28.3889 | 33.7303 | 33.7787 | 28.5290 |
| 3 | 73.8918 | 80.2785 | 80.2996 | 73.8938 |
| 4 | 142.2326 | 149.4281 | 149.4080 | 142.1568 |
| 5 | 260.4303 | 267.2562 | 267.1883 | 260.3188 |
| 6 | 415.6248 | 422.3192 | 422.2321 | 415.4292 |

The simulation results show that the dynamic response is mainly affected by the low-order frequency, so for the Timoshenko beam, after adding the deformation mode, although the beam has a greater range of deformation, and thus mixed space-time coupling produced a certain "softening" But the magnitude of the frequency is reduced. It is shown that in the generalized gyroscope G and the generalized stiffness matrix $K$ , the coupling term $\overline{W}_{21}, \overline{W}_{22}$ of the bending deformation is weak, and the coupling term in the longitudinal displacement and its D, C term in the generalized stiffness matrix $K$ Caused by the "power rigid" phenomenon is still more significant.

## 5.Application of Boltzmann Selection Mechanism in Cantilever Model of Flexible

In this paper, the model parameters of the plane redundant robot arm are as followed: ,the length of the manipulator is $L_1 = 1.2m, L_2 = 1m, L_3 = 0.6m, L_4 = 0.6m, L_5 = 0.4m$ ; the initial angle $\theta = [\frac{\pi}{8}, \frac{11\pi}{36}, \frac{5\pi}{9}, \frac{7\pi}{9}, -\frac{17\pi}{18}]$ the initial position of the robot arm terminal is $(0.6898m, 2.3824m)^T$, the robot arm terminal moves to $(2.3m, 2m)^T$, $(2m, 2m)^T$, $(1m, 2.8m)^T$, $(1.5m, 2m)^T$ four target location of the inverse solution. The objective function is optimized by the TVGSO algorithm, and the minimum value of the rotation angle $f_1$ is found in the 100 optimization results, and the optimal value of the rotation angle is obtained. Set the total exercise time to 1s after simulation. In the end of the arm to add the MARK point, the simulation can be measured from the initial position $(0.6898m, 2.3824m)^T$ moved to the target position of the trajectory curve, as shown in Figure 4 ~9.

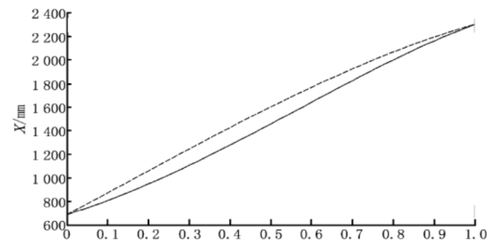


**Figure 4** X coordinate change curve when the target position is (2.3m, 2m)

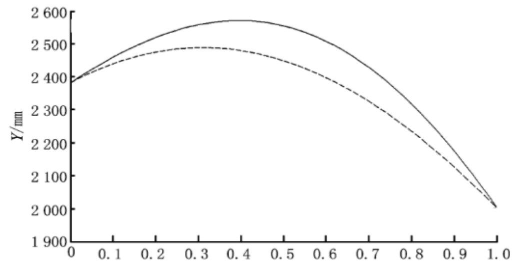


**Figure 5** Y coordinate change curve when the target position is (2.3m, 2m)

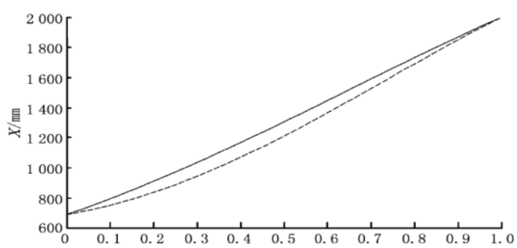


**Figure 6** X coordinate change curve when the target position is (2m, 2m)

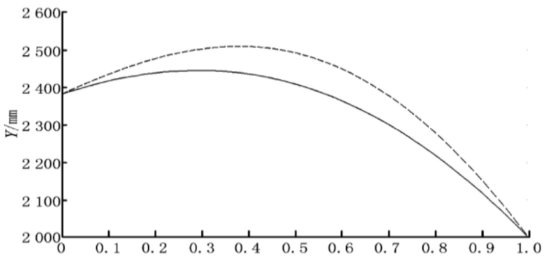


**Figure 7** Y coordinate change curve when the target position is (2m, 2m)

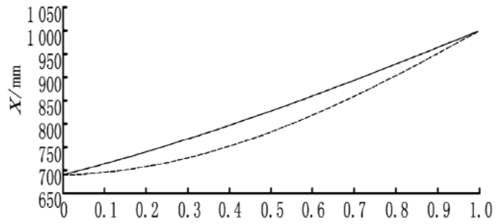

**Figure 8** X coordinate change curve when the target position is (1m, 2.8m)

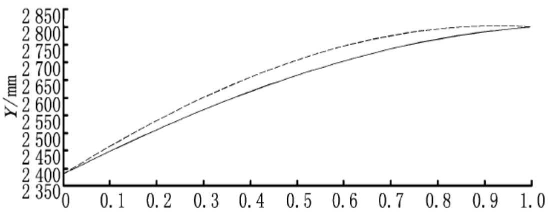

**Figure 9** Y coordinate change curve when the target position is (1m, 2.8m)

By using TVGSO algorithm to optimize the inverse of the arm of the plane redundant robot, the optimal rotation angle value of the end position and the expected position error is less than the given minimum value in the inverse of the arm of a plurality of planar redundant robots. Because this paper focuses on the inverse of the robot arm, so when the end position and the desired position error take the minimum value of the rotation angle $f_1$ value is relatively large. The simulation curves of the robot arm in ADAMS (Figure 4 ~ 9) verify the correctness and accuracy of the inverse solution. At the same time, the target position error optimized by comparing the TVGSO algorithm with the optimized GSO algorithm Target position error, it can also be seen that the TVGSO algorithm is superior to the GSO algorithm. Therefore, based on TVGSO algorithm to solve the redundant robot arm inverse solution is very effective. The error obtained by MATLAB simulation is somewhat different from the error $\Delta$ (ADAMS) and $\Delta$ (MATLAB) obtained by ADAMS simulation, which is caused by the limitation of $\pi$ (3.14159) and the number of effective digits of rotation angle.

## 6. Summary

In this paper, the flexible manipulator is regarded as the Euler-Bernoulli equal-section beam model with the existing cantilever of the ballastless trackless orbiter. The space independent parameters such as the natural frequency, the load impact and the axial deformation are the characteristic, A method of terminal vibration mechanism analysis based on time-varying glowworm swarm optimization algorithm is proposed.

Based on the nonlinear dynamic model, this paper proposes a TVGSO algorithm to apply to the split equation of the flexible cantilever operator. According to the boltzmann selection mechanism, the dynamic parameter in the motion simulation process is determined. Based on golden ratio segmentation ,the algorithm gives a time-varying strategy. The method is based on the change of the minimum distance between the glowworm individuals in the field, and the algorithm can satisfy the dynamic response and adaptability of the terminal vibration. The simulation results show that the method is effective and stable, and it has a great theoretical basis for the study of vibration control of flexible cantilever terminals.

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