Laser Detection Manipulator Stability Control Based on Inversion Control

Yan Ding, Kang Zhao, Zhongwei Ji and Tingrui Liu*
College of Mechanical & Electronic Engineering, Shandong University of Science & Technology, Qingdao 266590, China

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Abstract: In this paper, the trajectory tracking control problem of the laser detection manipulator based on inversion control adjusts the position of the camera under the movement of the 3R manipulator arm. Firstly, the 3D modeling software was used to build a structural model of the laser detection manipulator and describe the motion state of the manipulator arm. Secondly, according to the Lagrange dynamic theory, the driving moment of the three joints of the 3R manipulator arm was derived, the external interfering torque was introduced, and the dynamic model was established. An inversion controller of the system was then established based on the 3R manipulator arm dynamic model. Finally, the model was simulated by MATLAB, and the experimental results show that the control rate can achieve a good trajectory tracking goal.

1 INTRODUCTION

In recent years, with the continuous progress of science and technology, people's requirements for machines are getting higher and higher, the production and processing accuracy of machine parts is also getting higher and higher. In the process of parts processing and parts maintenance, in order to ensure that the accuracy of parts meets the requirements, it is often necessary to surface them quality inspection. The current detection method is mainly based on manual inspection and sampling inspection, large interferometers and small detectors. However, many existing detection instruments have the disadvantages of large size and immovability, and manual detection often faces a harsh environment and cumbersome detection steps, which is seriously affected Parts processing efficiency and increased labor costs. Therefore, the research of flexible and high-precision detection instruments has always been the focus of attention of experts in this field.

Motion control based on the 3R manipulator arm will be the key to solving the problem of efficient and stable detection of laser inspection manipulators. In the process of movement of multi-joint manipulator arms, due to the existence of external interference, there will often be a certain error in the movement of the manipulator arm, which will cause great trouble to the detection work requiring higher precision. In recent years of research at home and abroad, scholars have proposed some control methods, such as iterative control methods, sliding mode control methods, fuzzy control algorithms, etc. (Gao, 2022; Jin, 2018; Tian, 2021) to achieve the goal of anti-interference.

In previous studies, some scholars have divided the structure into three structures when analyzing the movement of the manipulator arm: "rigid linkage-flexible joint", "flexible linkage-rigid joint" and "flexible linkage-flexible joint" (Wu, 2021). The "flexible linkage" structure is generally suitable for long connecting rods and large linkage flexibility of the mechanical arm. For short and rigid linkages, its deformation due to its own flexibility during the movement is negligible. Kanellakopoulos (Kanellakopoulos, 1991) mentions an inversion control method that splits a complex system into simple subsystems that can control the tracking error to a very small extent, effectively implementing tracking control on the manipulator arm (Ruan, 2014). In this paper, a movable integrated laser detection manipulator is proposed, and the inversion control method is adopted for its motion control, which realizes the precise tracking control of the laser detection manipulator in adjusting the movement of the camera.

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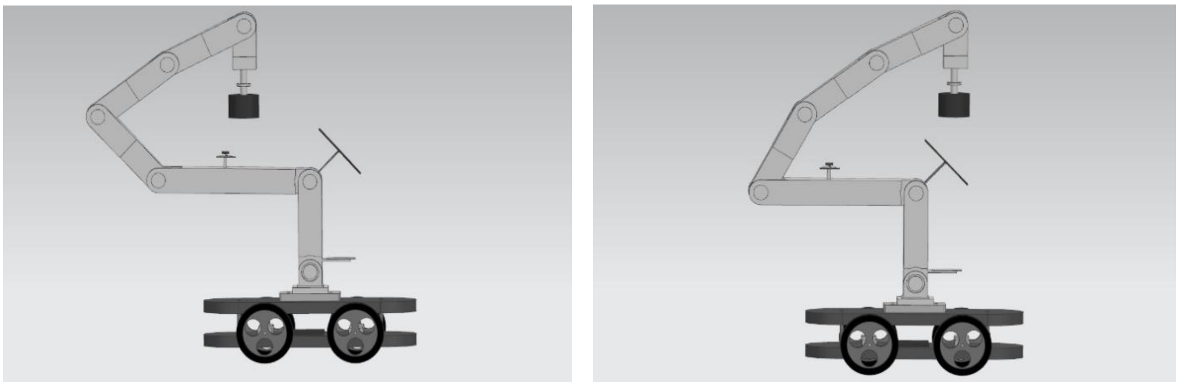


(a) Original location (b) Working position

Figure 1: Laser detection manipulator movement process.

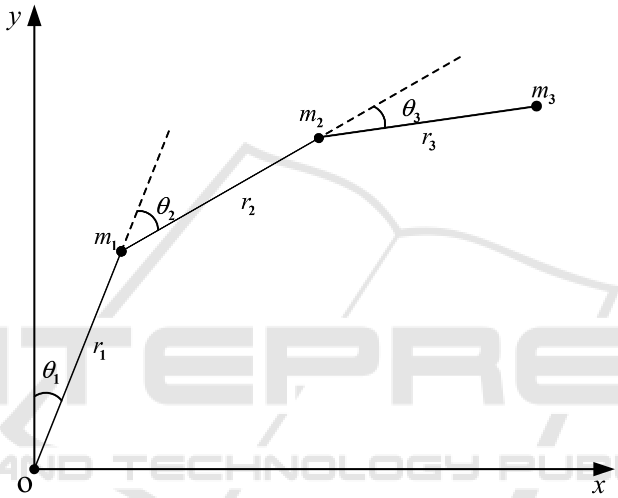


Figure 2: Brief diagram of the 3R manipulator arm mechanism.

2 MODELING OF THE STRUCTURE OF THE LASER INSPECTION MANIPULATOR

When the laser inspection manipulator performs the inspection task, it is necessary to adjust the position of the camera to meet its requirements directly above the beamsplitter. Figures 1 (a)-(b) depict the process of simulating the manipulator's movement from its original position to its working position through UG modeling.

In the process of laser manipulator moving towards the workpiece under test, due to inertia and other external disturbances, the position of each manipulator arm in the working position often changes, especially at the three manipulator arms that control the position of the camera. Therefore, this paper mainly uses the three manipulator arms as research objects to analyze the motion and control problems of laser detection manipulators. A schematic diagram of the mechanism of the three-degree self-restraint manipulator arm studied is shown in Figure 2.

Based on the Lagrange dynamics, the 3R manipulator arm dynamics equation is established, and the driving moments of the three moving joints τ_1, τ_2 and τ_3 the sum, are as follows:

$$\begin{aligned}\tau_1 = {} & (m_1+m_2+m_3)r_1^2\ddot{\theta}_1 + (m_2+m_3)r_1r_2\ddot{\theta}_2\cos(\theta_1-\theta_2) + (m_2+m_3)r_1r_2\dot{\theta}_2^2\sin(\theta_1-\theta_2) \\ & + m_3r_1r_3\ddot{\theta}_3\cos(\theta_1-\theta_3) + m_3r_1r_3\dot{\theta}_3^2\sin(\theta_1-\theta_3) + (m_1+m_2+m_3)gr_1\cos\theta_1\end{aligned} \tag{1}$$

$$\tau_2 = (m_2+m_3)r_2^2\ddot{\theta}_2 + (m_2+m_3)r_1r_2\ddot{\theta}_1\cos(\theta_1-\theta_2) - (m_2+m_3)r_1r_2\dot{\theta}_1^2\sin(\theta_1-\theta_2) + m_3r_2r_3\ddot{\theta}_3\cos(\theta_2-\theta_3) + m_3r_2r_3\dot{\theta}_3^2\sin(\theta_2-\theta_3) + (m_2+m_3)gr_2\cos\theta_2 \tag{2}$$

$$\tau_3 = m_3r_3^2\ddot{\theta}_3 + m_3r_1r_3\ddot{\theta}_1\cos(\theta_1-\theta_3) - m_3r_1r_3\dot{\theta}_1^2\sin(\theta_1-\theta_3) + m_3r_2r_3\ddot{\theta}_2\cos(\theta_2-\theta_3) - m_3r_2r_3\dot{\theta}_1^2\sin(\theta_2-\theta_3) + m_3gr_3\cos\theta_3 \tag{3}$$

Considering the interference moment, apply the kinetic equation Eq. (1)-Eq. (3) Simplified to:

$$M_N\ddot{I} + D_N\dot{I} + K_N + \tau_e = \tau \tag{4}$$

where M_N is the inertia matrix, D_N is the centrifugal force and the Gossonian force vector, K_N is the gravitational vector, τ_e is the interference moment vector, τ is the joint driving torque vector, I is the vector of the joint angle variable.

3 CONTROLLER DESIGN

3.1 Equations of State Space

Kinetic equation Eq. (4) Consider $I_1 = \begin{bmatrix}\theta_1 & \theta_2 & \theta_3\end{bmatrix}^T$ and $I_2 = \begin{bmatrix}\dot{\theta}_1 & \dot{\theta}_2 & \dot{\theta}_3\end{bmatrix}^T$, then the equation of its state-space form is:

$$\begin{cases}\dot{I}_1 = I_2 \\ \dot{I}_2 = -U\dot{I}_1 - R - P + Cu\end{cases} \tag{5}$$

where $U = M_N^{-1}D_N, R = M_N^{-1}K_N, P = M_N^{-1}\tau_e, C = M_N^{-1}$, $u=\tau$.

3.2 Invert the Controller Design

By introducing the desired trajectory, designing an inversion controller, and controlling the change of the driving torque, the purpose of tracking control is achieved.

Set the error vector of the system E to:

$$E = A - I_1 = \begin{bmatrix}e_1 & e_2 & e_3\end{bmatrix}^T = \begin{bmatrix} i_{1d}-\theta_1 \\ i_{2d}-\theta_2 \\ i_{3d}-\theta_3\end{bmatrix} \tag{6}$$

where $A = \begin{bmatrix}i_{1d} & i_{2d} & i_{3d}\end{bmatrix}^T$ is the desired state trajectory.

The error vector is derived and combined with Eq. (5) to obtain:

$$\dot{E} = \dot{A} - \dot{I}_1 = \dot{A} - I_2 \tag{7}$$

Build Lyapunov function:

$$V_1 = \frac{1}{2}E^TE \tag{8}$$

Derive it and bind it to Eq. (7) to obtain:

$$\dot{V}_1 = E^T\dot{E} = E^T\left(\dot{A} - I_2\right) \tag{9}$$

According to the Lyapunov stability principle, V_1 is positive and $\dot{V}_1$ is negative.

$$\dot{A} - I_2 = -k_1E \tag{10}$$

where $k_1 > 0$.

combine it with Eq. (9) to obtain:

$$\dot{V}_1 = -k_1E^TE < 0 \tag{11}$$

Set the error vector of the system as:

$$F = H - I_2 \tag{12}$$

Make the second desired trajectory is $H = I_2$, combine it with Eq. (10) to obtain:

$$H = \dot{A} + k_1E \tag{13}$$

Build Lyapunov function:

$$V_2 = V_1 + \frac{1}{2}F^TF \tag{14}$$

Derive it and bind it to Eq. (11) to obtain:

$$\dot{V}_2 = -k_1 E^T E + F^T\left(E + \dot{F}\right) \tag{15}$$

According to Lyapunov's stability theorem, we can know $\dot{V}_2$ is negative.

$$E + \dot{F} = -k_2 F \tag{16}$$

where $k_2 > 0$ and consider Eq. (15) to obtain:

$$\dot{V}_2 = -k_1 E^T E - k_2 F^T F < 0 \tag{17}$$

The controller system meets the stability conditions of Lyapunov, when the desired trajectory is A set to the origin, and the asymptotic F is stable at the origin, it can be guaranteed that I_2 and I_1 approache tracking trajectory gradually.

Derive Eq. (12) and bind it to Eq. (5) and Eq. (16) to obtain:

$$\dot{F} = \dot{H} - \dot{I}_2 = \dot{H} - \left(-U\dot{I}_1 - R - P + Cu\right) = -E - k_2 F \tag{18}$$

Then the inversion control rate is:

$$u = C^{-1}\left(E + \dot{H} + k_2 F + U\dot{I}_1 + R + P\right) \tag{19}$$

4 SIMULATION ANALYSIS

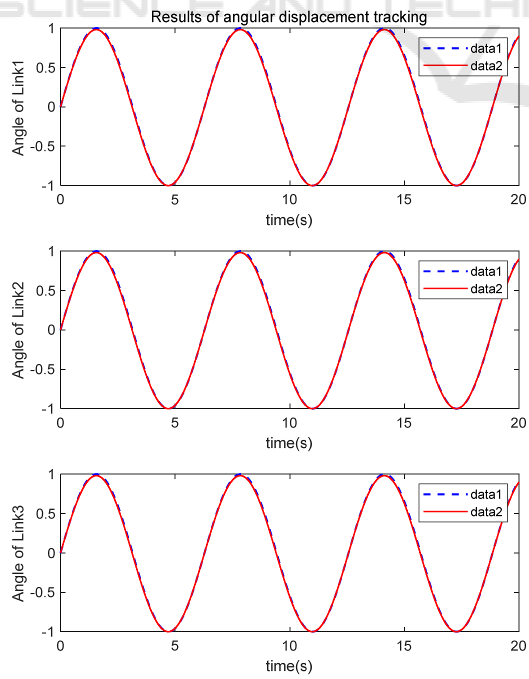
Adding the inversion control rate obtained above, this article uses the 3R manipulator arm shown in Figure 2 as the control object for MATLAB simulation analysis (Xue, 2007; Liu, 2016).

The structural parameters of the 3R manipulator arm are shown in Table 1.

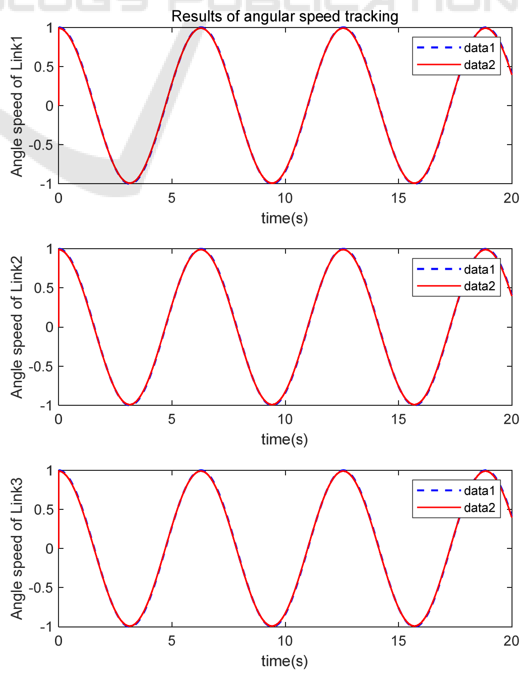
Suppose the desired trajectory of the three joints is $A = [sin(t) \quad sin(t) \quad sin(t)]^T$, the interference torque is $\tau_e = [1.2\,sin(t) \quad 1.2\,sin(t) \quad 1.2\,sin(t)]^T$, and the controller controls the parameters are $k_1 = k_2 = 1\sim100$. The simulation results are shown in Figure 3.

Table 1: 3R manipulator arm structure parameters.

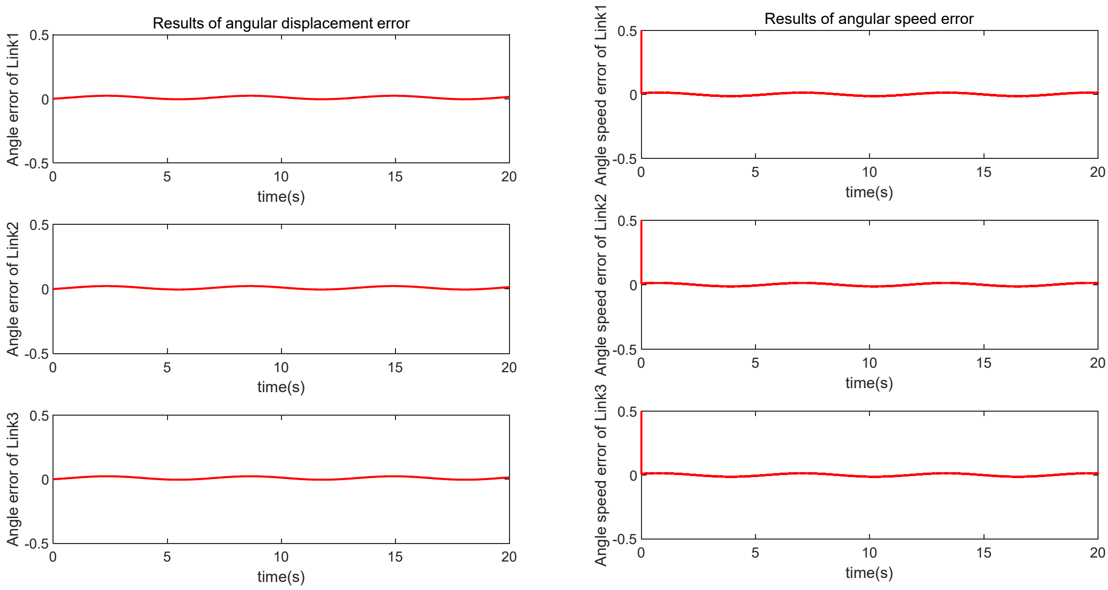
Joint	quality	length	Rotation angle
Joint 1	$1.0kg$	$0.5m$	θ_1
Joint 2	$1.0kg$	$0.5m$	θ_2
Joint 3	$3.0kg$	$0.5m$	θ_3



(a) Angular displacement trajectory tracking



(b) Angular velocity trajectory tracking



(c) Angular displacement tracking error

(d) Angular velocity tracking error

Figure 3: Simulation diagram of trajectory tracking of 3R manipulator arm based on inversion control.

From the simulation analysis diagram, it can be seen that the inversion controller can effectively control the manipulator arm to track the desired trajectory, the angle tracking and angular velocity tracking effect of joint 1, joint 2 and joint 3 is obviously very good, the angle tracking error can always be controlled within $0.024m$, and the angular speed tracking error can be controlled within $0.015m$. Inside, the controller can effectively overcome external interference, so that the laser inspection manipulator can smoothly and accurately carry out inspection operations.

5 CONCLUSION

In this paper, the upper three arms of the laser detection manipulator are used as the research object, and the dynamic equation of the 3R manipulator arm is established based on the Lagrange dynamic theory, and the inversion control method is adopted, the inversion controller of the motion system is designed, and its stability is verified. The motion control of the 3R manipulator arm is simulated by MATLAB simulation software, and the simulation results show that the controller designed in this paper can effectively achieve the goal of trajectory tracking and stabilize the error within the effective range. This testifies the feasibility of the control law of the design, and provides a rich theoretical basis for the future research on improving the detection accuracy and fast and smooth motion of laser detection manipulators.

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REFERENCES

Gao Y, Wei W, Wang X, Wang D, Li Y and Yu Q 2022 *Information Sciences* 606 489-511.

Jin X 2018 *Automatic* 94 63-71.

Tian Y, Huo Z, Wang F and Shi B 2021 *Sensors and Actuators A: Physical* 331 112959.

Kanellakopoulos I, Kokotovic P, Morse A 1991 *IEEE Transactions on Automatic Control* 36 1241-1253.

Ruan Y, Wang W 2014 *Journal of Minjiang University* 35 67-73.

Wu K 2021 *Taiyuan University of Technology*.

Xue D 2007 *MATLAB Solutions to Mathematical Problems in Control* (Beijing: Tsinghua University Press) chapter 4 pp 198–210.

Liu J 2016 *Robot Control System Design and MATLAB Simulation the Basic Design Method*(Beijing: Tsinghua University Press) chapter 6 pp 152–162.