Intelligent control of a large underwater tunnel sinking pipe hoisting manipulator

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Abstract. To improve the intelligence of sinking pipe hoisting in the underwater tunnel, an intelligent mechanical arm is used for hoisting control. This paper presents an intelligent control technique based on loading of load transfer mechanism and state feedback regulation without joint for lifting and hoisting manipulator of large underwater tunnel. This paper analyzes the technical preparation flow and key technology of the lifting of large underwater tunnel pipe sinking, and constructs the constraint parameter model of the pressure control of the pipe sinking pipe hoisting arm of the large underwater tunnel. The load-transfer mechanism of large underwater tunnel sinking pipe hoisting manipulator is analyzed, and the moving platform and power driving unit of hoisting arm are established. Combined with the compensation method of end position and attitude parameters of multi-joint tracking, the pressure bearing mechanical control of large underwater tunnel sinking pipe hoisting mechanical arm is carried out, and the control law of large underwater tunnel sinking pipe hoisting robot arm is constructed by using finite element dynamic analysis method. The pressure torque control of large underwater tunnel pipe hoisting mechanism arm is realized, and the position and pose adjustment ability of large underwater tunnel sinking pipe hoisting is improved, and the docking error of sinking pipe hoisting is reduced. The simulation results show that this method has good stability for intelligent control of large underwater tunnel sinking pipe hoisting manipulator, and the accuracy of position and pose tracking for large underwater tunnel sinking pipe hoisting process is high. The safety and intelligence of sinking pipe hoisting in the underwater tunnel are improved.

1. INTRODUCTION
With the rapid development of social economy, the demand of cross-sea passage is increasing. Bridges and tunnels are usually used to cross the sea. However, with the improvement of ecological environment and the rapid development of ship tonnage, the conditions of bridge construction are becoming more and more harsh. The construction of underwater tunnel has made a flying development. At present, the methods of constructing underwater tunnel include mine method, shield method, cofferdam excavation method and sinking pipe method. Pipe sinking method is a new kind of underwater tunnel construction method developed at the beginning of the 20th century. With its advantages of shallow buried depth, large section and good waterproof effect, the construction of submerged tunnel has made a rapid development with the development of engineering technology[1].
Pipe sinking method is also called precast pipe section sinking method, which simply means prefabricating large concrete box members or composite box members of concrete and steel in dry dock or on the berth, and closing them with temporary partition walls at both ends for outfitting and towing. Locate the equipment, then float and sink the components in the pre-dredged trench on the riverbed and connect them together. Finally, fill the sand back and remove the partition wall to form a tunnel. The way combined with the hoisting of mechanical arm is greatly affected by the complex environment of the dock, especially by the disturbance of the output moment of the manipulator. During the hoisting process, it is easy to occur some accidents, such as displacement of position and posture, collision and so on. In order to improve the intelligent control ability and anti-disturbance ability of the large underwater tunnel sinking pipe arm, an intelligent control method for lifting and installing the large underwater tunnel pipe sinking manipulator is needed to optimize the intelligent control system of the manipulator. In the traditional methods, the main control methods for hoisting manipulator are fuzzy control model, PID control model, sliding mode integral control method. The sensor fusion tracking control model and pressure sensing control model are constructed[2-4], combined with the control force parameter analysis of the manipulator and the load-bearing force analysis of the manipulator, a fuzzy control method is adopted to realize the lifting control of the large underwater tunnel sinking pipe arm. In reference [5], a pressure control method based on aerodynamic damping coupling compensation for lifting manipulator of large underwater tunnel is proposed. The coupling control system of multi-variable coupling control system is used to control the coupling of hoisting manipulator. The intelligent distribution ability of the load-bearing force of the manipulator is improved, but the anti-disturbance ability of the control method is not good.

Aiming solve the above problems, this paper presents an intelligent control technique based on load-transfer mechanism loading and no-joint state feedback regulation for lifting and hoisting manipulator of large underwater tunnel. Firstly, the technical preparation flow and key technology of the lifting of large underwater tunnel sinking pipe are analyzed. Then the finite element dynamic analysis method is used to construct the control law of the lifting and mounting mechanical arm of the large underwater tunnel pipe sinking pipe to realize the pressure moment control of the large underwater tunnel pipe sinking pipe hoisting manipulator arm. Finally, the simulation results show that the proposed method can improve the intelligent control ability of large underwater tunnel pipe hoisting manipulator.

2.GENERAL DESIGN OF SINKING PIPE HOISTING TECHNOLOGY FOR LARGE UNDERWATER TUNNEL
The technical index of lifting and launching the sinking pipe of this type of large underwater tunnel is researched, this paper first analyzes the overall process of lifting and installing the sinking pipe of the large underwater tunnel. After the preparation of the technical position for the sinking pipe of the large underwater tunnel is completed, each segment, system and main component of the tunnel is combined and tested to complete the synthesis of the whole cabin segment of the vehicle. In the past, the water through the tunnel is generally about 1Km, the pipe section is integrated, the integral pipe section is subjected to longitudinal force, and the joint is subjected to seismic resistance. Due to the influence of deformation and other factors, the length of pipe section is generally about 100m, but as the width of the tunnel across the water area becomes wider and larger, the adoption of integral pipe section will greatly increase the floating transportation of the project. In 2000, the Erlerian Channel Tunnel between Denmark and Sweden was constructed in the form of a segmental reinforced concrete pipe segment, the length of which was 175m. It consists of 8 segments, each of which is 22 m in length. The rubber water stop belt is used between the pipe segment and the pipe segment, and the longitudinal prestressed steel cable connection is adopted between all the pipe segments to form a whole. In the design of the segmental pipe segment, according to the seismic design of the segment joint and the pipe joint, the longitudinal and lateral forces under each working condition are analyzed to determine synthetically[6].
3. Kinematics Model and Mechanical Parameter Analysis of the Lifting Manipulator for Large Underwater Tunnel Sinking Pipe

3.1 Kinematics Model of Lifting Manipulator for Sinking Tube of Large Underwater Tunnel

In order to realize the stable control of large underwater tunnel sinking pipe hoisting manipulator, the inertial attitude fusion space kinematics model of large underwater tunnel sinking pipe hoisting manipulator is constructed. It is necessary to plan 7 degrees of freedom motion space of large underwater tunnel sinking pipe hoisting manipulator, and design 7 rotational freedom motion models of large underwater tunnel sinking pipe hoisting robot arm. The terminal position and attitude estimator is used to collect the attitude characteristic sensing and control constraint parameter analysis of large underwater tunnel sinking pipe hoisting manipulator. The intelligent control of hoisting manipulator is based on the collection of working environment parameter information and the analysis of mechanical sensing information [7]. The mechanical data collection and measurement of large underwater tunnel sinking pipe hoisting manipulator are carried out by distributed sensor array, and the inertial pressure bearing mechanics analysis of large underwater tunnel sinking pipe hoisting manipulator is carried out by using sensitive element. The large underwater tunnel sinking pipe hoisting manipulator studied in this paper is a multi-stage gravity lifting manipulator. In this paper, the pressure bearing mechanics model of large underwater tunnel pipe hoisting manipulator is analyzed and calculated by using Numeca Fine/Turbo software, and the coupling multi-body dynamics model of large underwater tunnel sinking pipe hoisting robot arm is established. By solving the mechanical characteristic equation, the characteristic parameter model of large underwater tunnel sinking pipe hoisting manipulator is obtained, and the basic geometric parameters of pressure control of large underwater tunnel sinking pipe hoisting machine arm are obtained as shown in Table 1.

| Parameter name                  | Parameter values |
|---------------------------------|------------------|
| Position error                  | 254              |
| Bending degree                  | 45.43            |
| Pressure radians                | 4.654            |
| Curvature difference            | 2.43             |
| Midpoint cone distance          | 8.56             |
| Large end modulus               | 24               |
| Midpoint helical angle          | 23.465           |

According to the constraint parameter model in Table 1, the pressure control object model of the lifting arm of large underwater tunnel is established [8]. Under the action of pressure sensing, the modal parameter identification model of the pressure of sinking pipe hoisting mechanical arm in the underwater tunnel is expressed as follows:

\[
X(n) = [x_1(n), x_2(n), ..., x_m(n)]^T, \\
W_j(n) = [w_1(n), w_2(n), ..., w_m(n)]^T, j < m, \\
a_j(n) = [a_1(n), a_2(n), ..., a_m(n)]^T, j < m, \\
Y_{ji}(n) = [y_1(n), y_2(n), ..., y_m(n)]^T, j < m.
\]

(1)

According to the identification parameter model of pressure control, the finite element analysis model of pressure control for large underwater tunnel sinking pipe hoisting manipulator is obtained.

3.2 Analysis of Load-Transfer Mechanism Bearing Capacity of Hoisting Manipulator

In this paper, a constraint parameter model of the pressure control of the sinking pipe hoisting machine arm of a large underwater tunnel is constructed, and the load-transfer mechanism of the large underwater tunnel pipe hoisting arm is analyzed. According to the finite element analysis model of pressure control of large underwater tunnel sinking pipe hoisting arm, the characteristic data of
The characteristic matrix $R$ is defined as:

$$R = X(n)X^T(n) = 
\begin{bmatrix}
x_1(n)x_1(n) & x_1(n)x_2(n) & \ldots & x_1(n)x_m(n) \\
x_2(n)x_1(n) & x_2(n)x_2(n) & \ldots & x_2(n)x_m(n) \\
\vdots & \vdots & \ddots & \vdots \\
x_m(n)x_1(n) & x_m(n)x_2(n) & \ldots & x_m(n)x_m(n)
\end{bmatrix} \quad (2)$$

Based on the load transfer mechanism model, the dynamic geometric characteristic parameters of the lifting arm of a large underwater tunnel are sorted. The stress yield response distribution of the lifting manipulator can be expressed as follows:

$$\lambda_1 > \lambda_2 > \ldots > \lambda_{j-1} > \lambda_j > \ldots > \lambda_m \quad (3)$$

According to the bearing capacity of the load transfer mechanism for lifting the arm of a large underwater tunnel, the control parameter model of the arm is obtained as follows:

$$\sum_{k=1}^{m} [\theta_{\beta}(n+1) - \theta_{\beta}(n)]q_k = 0$$
$$\sum_{k=1}^{m} \eta_{\alpha}(n)\theta_{\beta}(n)q_k + n\sum_{k=1}^{m} \lambda_{\alpha}(n)q_k \quad (4)$$

According to the velocity and acceleration of hoisting manipulator in motion, combined with the flexible driving analysis method, the load distribution model between the connecting rods of the large underwater tunnel sinking pipe hoisting arm is constructed. The load-transfer mechanism model is designed to improve the intelligent control ability of large underwater tunnel sinking pipe hoisting manipulator\(^[9]\).

4. OPTIMAL DESIGN OF CONTROL LAW FOR MANIPULATOR

On the basis of constructing the constraint parameter model of the pressure control of the sinking pipe hoisting manipulator in the large underwater tunnel and carrying out the load-transfer mechanism analysis of the large underwater tunnel sinking pipe hoisting arm, the optimal design of the control law of the manipulator is carried out. In this paper, an intelligent control technique for lifting manipulator of large underwater tunnel pipe sinking based on loading of load transfer mechanism and state feedback regulation without joint is proposed, which adaptively adjusts the bearing direction of the lifting arm. Adaptive pressure regulation and feedback control are carried out to improve the load transfer control ability of large underwater tunnel sinking pipe hoisting manipulator\(^[10]\). The parameter identification of load transfer mechanism model of large underwater tunnel sinking pipe hoisting manipulator is carried out, and the inverse Jacobian matrix of loading moment is obtained as follows:

$$v^T_{i-1} =
\begin{bmatrix}
c\theta & -s\theta & 0 & a_{i-1} \\
s\theta c\alpha_1 & c\theta c\alpha_1 & -s\alpha_1 & -d_s\alpha_1 \\
s\theta s\alpha_1 & c\theta s\alpha_1 & c\alpha_1 & d_c\alpha_1 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (5)$$

Under continuous driving, the disturbance torque of large underwater tunnel pipe hoisting manipulator is $\omega(k)$. In the 6-DOF space model, the axial pressure transformation matrix of large underwater tunnel sinking pipe hoisting manipulator is obtained:

$$^0_6T = ^0_2T + ^3_4T + ^0_1T + ^1_6T \quad (6)$$

The identification parameters of pressure control of large underwater tunnel pipe hoisting manipulator are analyzed, $m_j(j=1,2,\ldots,m) \ \forall m_j \in M$, combined with multi-joint tracking compensation method of end-position and attitude parameters is used to control the pressure bearing mechanical control of large underwater tunnel pipe hoisting robot arm. The structural distribution and related parameter models are obtained as follows:
The identification parameters of pressure control of large underwater tunnel pipe hoisting manipulator are analyzed, \( m_j(j=1,2,\ldots,m) \ \forall m_j \in M \), combined with multi-joint tracking compensation method of end-position and attitude parameters is used to control the pressure bearing mechanical control of large underwater tunnel pipe hoisting robot arm. The structural distribution and related parameter models are obtained as follows:

\[
u_{ij}(k-1/k-1) = P(m(k-1)/m(k), z^{i+1}) = \frac{1}{\epsilon} P_m(k-1) \tag{7}\]

By introducing the adaptive adjustment coefficient of loading force, the driving equation of bearing capacity of large underwater tunnel sinking pipe hoisting manipulator is obtained as follows:

\[
\dot{x}_j(k/k) = \sum_{j} \dot{x}_j(k/k)u_j(k) \tag{8}
\]

\[
P(k/k) = \sum_{j} u_j(k/k)\{P_j(k/k) + [\dot{x}_j(k/k) - \dot{x}(k/k)][\dot{x}_j(k/k) - \dot{x}(k/k)]^T\} \tag{9}\]

Ignoring the influence of dynamics and motion control system of large underwater tunnel sinking pipe hoisting robot arm, combined with multi-joint tracking end position and attitude parameter compensation method, the pressure bearing mechanical control of large underwater tunnel sinking pipe hoisting robot arm is carried out. The mechanical spatial distribution function of the manipulator is obtained as follows:

\[
KL = \sum_{i=1}^{n} \frac{1}{N} \ln \frac{1}{N} \sum_{i=1}^{n} (1-K_{d_i}^{max}) \tag{10}\]

The finite element dynamic analysis method is used to construct the control law for the lifting and mounting manipulator of large underwater tunnel. The combined control term of loading force and torque is \( \{W_{final}\} \), and the characteristic parameter of controller is as follows:

\[
\{W_{final}\} = \{x_{f_{final}}\} = \{\frac{1}{N} \sum_{i=1}^{n} x_{11}, 1, \frac{1}{N} \sum_{i=1}^{n} (1-K_{d_i}^{max}), x_{21}, 1, \frac{1}{N} \sum_{i=1}^{n} K_{d_i}^{max}, x_{21}\} \tag{11}\]

The Lyapunov function of hoisting manipulator is constructed as follows:

\[
V_2 = V' + \frac{1}{2} e^2 \tag{12}\]

Finding derivatives for Lyapunov functions:

\[
\dot{V}_2 = V_2 + e \dot{e} \tag{13}\]

According to the principle of Lyapunov stability, the stability of the control law designed in this paper is obtained. By introducing the load force vector of the manipulator, the steady-state error compensation term of the large underwater tunnel sinking pipe hoisting manipulator is obtained as follows:

\[
\theta = -\hat{\theta}(\alphaV^2 + mg(\sin \theta + V \omega_2) + m(\cos \theta + V \omega_2) + c_1e_2 + \lambda_1e_1 - e^2) \tag{14}\]

When \( \theta = \pm 90^\circ \), the lifting position of sinking pipe in the underwater tunnel is corrected, the error of position and pose adjustment is reduced, and the adjustment ability of lifting and installing of sinking pipe in the underwater tunnel is improved.
5. SIMULATION EXPERIMENT AND RESULT ANALYSIS

In order to test the application performance of this method in the intelligent control of a large underwater tunnel sinking pipe hoisting robot arm, the simulation experiment is carried out. The experiment is designed by Matlab 7, and three-axis electronic compass LSM303DLH is used to collect the attitude sensing data of large underwater tunnel sinking pipe hoisting manipulator. The period of acquisition of position and attitude parameters of lifting manipulator is 0.56 s, the scale of test set of attitude sensor data sample is 2000, the scale of training data set is 100, the diameter of sinking tube of large underwater tunnel is set to 324mm, the maximum torque is set to 28KN, and the center of gravity moves down. According to the simulation environment and parameters mentioned above, the quantity is 2mm and the static inclination is set to 10°. The control simulation of the lifting arm of the large underwater tunnel sinking pipe is carried out, and the result of the sensing mechanical parameter acquisition of the large underwater tunnel sinking pipe hoisting manipulator is shown in figure 1.

![Figure 1. Acquisition of mechanical parameters of large underwater tunnel sinking pipe hoisting manipulator](image1)

With the data collected in figure 1 as the control input, the intelligent control of the manipulator is carried out, and the control output torque of the hoisting manipulator is obtained as shown in figure 2.

![Figure 2. Control output torque of hoisting manipulator](image2)

Figure 2 shows that the control method designed in this paper has good mechanical performance and good convergence of torque output for lifting and installing sinking pipes in the underwater tunnels. Different methods are used to test, and the control convergence curves are compared as shown in Fig. 3. The analysis figure 3 shows that the intelligent control of large underwater tunnel sinking pipe hoisting manipulator using this method has good convergence. The intelligent control of large underwater tunnel sinking pipe hoisting robot arm is more stable, and the accuracy of position and pose tracking of large underwater tunnel sinking pipe hoisting process is higher, which improves the safety and intelligence of large underwater tunnel sinking pipe hoisting.
6. CONCLUSIONS

In this paper, an intelligent control technique for lifting large underwater tunnel pipe sinking manipulator is proposed based on loading of load transfer mechanism and state feedback regulation without joint. The moving platform and dynamic driving unit of hoisting manipulator are established. Combined with the compensation method of end position and attitude parameters of multi-joint tracking, the pressure bearing mechanics control of large underwater tunnel lifting and installing manipulator is carried out. The finite element dynamic analysis method is used to construct the control law of the lifting and mounting mechanical arm of the large underwater tunnel pipe. The pressure moment control of the large underwater tunnel pipe sinking pipe hoisting arm is realized. The automatic adjustment ability of the position and orientation of the sinking pipe hoisting in the large underwater tunnel is improved. The accuracy of position and pose tracking for large underwater tunnel sinking pipe hoisting process is high. The safety and intelligence of sinking pipe hoisting in the underwater tunnel are improved. This method has good application value in intelligent control of tunnel sinking pipe hoisting manipulator.

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