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Research On End Trajectory Tracking Algorithm Of Dual-Manipulator Coordination Control Based On MPC Method

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ABSTRACT: *This paper presents a master-slave position coordinated control method based on model predictive control algorithm (MPC), to improve the trajectory tracking accuracy of slave arm according to the master arm end position when two manipulators are coordinating motion to execute welding tasks. Position control is adopted for master arm and position control based on MPC algorithm is adopted for the slave one where a distance measuring sensor with 3D laser scanner is installed in the end position to obtain position and direction information of master arm; On the basis of rotation operation sequence of joint angle transformation and predictive model of end position for manipulators, the current position state and the position input state of next step will be used for predicting position output state during some future time domain with dynamic matrix control algorithm, to realize the desired trajectory tracking. Finally, simulation testing for effectiveness of this algorithm was implemented, and then result shows that slave arm can more effectively realize real-time tracking desired trajectory according to dynamic information from the end position of master arm.*

KEY WORDS: *Dual manipulators; model predictive control; master-slave position coordinated control; trajectory tracking*

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I. INTRODUCTION

With the development of industrial technology, traditional single-arm robot just can handle simple tasks, but not useful to specific requirements. Thus, dual-arm robot system can handle more complex tasks with more advantages, such as higher flexibility, larger work space and more motion range, which improve the ability of handling tasks, loading capacity and working efficiency for robots. Therefore, the use of dual-arm robots coordination tasks is increasing in industrial field. However, under various expected disturbances in different environments, the control of dual-arm robots coordination motion seems even more important for welding tasks. Coordination control for dual-arm robots is to obtain better manipulating objectives with much advantages, while complex systems will be presented at the same time, with more complexity of analyzing and control problem. Hogan presented that impedance control algorithm could be used between end effector and working environment, with setting position deviation and contact force for manipulators to keep the mechanical impedance relationship, which shows the flexibility of dual-manipulator system[1]. However, the article[2] pointed out this method is just suitable for some flexible objectives with constraints under specific conditions. Seul proposed the improvement based on the previous research by Hogan that position control algorithm and impedance control algorithm are combined to offset uncertain dynamics equation by sampling points of torque compensation information, which use the coordinate position instead of cooperative control[3]. Claudio G et al combined master-slave coordination control with computer vision to track manipulator action by vision sensors and simultaneously make manipulators perform coordination motion by computational analysis[4]. Huang presented adaptive sliding mode control algorithm, which can guarantee stability of system with parameter variations and collision influence, while the maximum value of each matrix in dynamic model should be estimated, so it is difficult to be applied in reality[5]. Aghili pointed out an adaptive coordination controller which could handle accurate control problems for manipulator movement without position and direction information. The main advantage of this controller is no need of using contact force measurement to make geometric compensation and no need to make calibration by high-precision sensors[6]. Wei Cheng presented a coordination control method combining force-position control and master-slave control where predictive model is built by force signals from force sensors. The relationship of the position of each fingers on manipulator and the force acted on objectives is built by force controller, which can adjust the weight of current-future force errors automatically according to model accuracy[7]. To solve the problem of dual-manipulator high-precision coordination welding, this paper presents the master-slave position hybrid coordination control method based on model predictive control algorithm. When manipulators execute welding tasks, master manipulator will be assigned main movement plan and simultaneously the position sensor on the end of slave manipulator will obtain position signal of master manipulator to make prediction of the output state of manipulator end when moving. The error between actual position output and predictive position output will be adjusted by error weight according to the model accuracy, in order to improve the tacking accuracy of slave manipulator towards expected trajectory and reduce impacts of time delay on control system.

1. Dual-manipulator coordination control algorithm and interrelationship

At present, coordination control strategies for dual manipulators mainly consist of master-slave coordination control, position-position control, force-position control and impedance control. In terms of cooperative welding, this paper adopts hybrid control strategy combining mater-slave coordination control with position-position control that position control is adopted for master manipulator but position control based on dynamic matrix control algorithm, one of the classic model predictive control algorithms, is used for the slave one[8], as shown in Figure1.

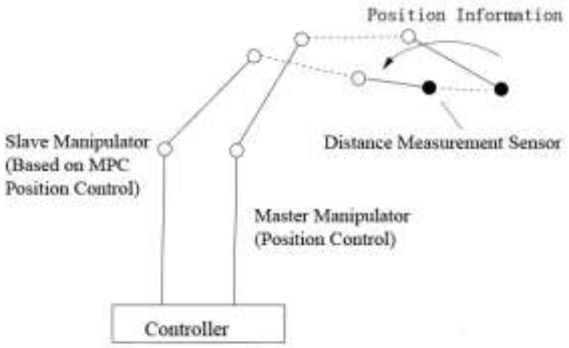

Figure1 Master/slave manipulators control schematic

1.1 Master-slave control

During many coordination control strategies, master-slave control was proposed as a kind of control methods for dual-robot system in early researches, where there is no need to consider the dynamics model of whole coordination system[9]. During the process of coordination motion, the master-manipulator trajectory will be assigned according to manipulating objective, with requirement to remain relative position and direction between the ends of master and slave manipulators unchanged. In master-slave mode, a distance measuring sensor with 3D laser scanner is installed on the end of manipulators, through which position information will be transmitted to master manipulator and slave manipulator can realize coordination movement according to the position relationship of measurement. With respect to control feedback, distance measuring sensor of slave manipulator will be used to track master-manipulator trajectory in all directions. Therefore, master-slave coordination control is usually adapted for loose-coupling coordination welding or tight-coupling coordination rigid-objective carrying tasks.

1.2 Position-position control

When master manipulator executes tasks following the panning trajectory, the slave one will move along motion trajectory by master manipulator, which could realize the master-slave manipulators coordination control. In addition, this coordination motion falls under non-rigid coupling, which means no acting force between two manipulators, and the manipulators remain under low-medium speed when executing whole welding tasks. Thus, there is no need to consider the problem relative to force control of the manipulator end in this paper, so position-position control is chosen as control method. In close-loop control law, position-position control synthesizes the position information of dual-manipulator ends. During executing welding tasks, there will be relative movement between the manipulator end and objective as well as between two manipulators, and thus, if the relative position between dual-manipulator ends remain unchanged, then manipulating-objective position will not change. Therefore, position control for slave manipulator end depends on master one.

1.3 Interrelationship of dual-manipulator coordination motion

In this paper, two 6-DOF manipulators are chosen as dual arms with position control. Thus, transformation relationship between end position and joint angles can be built by kinematics model of manipulator, with a set of joint angles, $(\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6)$, to identify the end position and posture of manipulator which can be expressed as position vector, $P = (p_x \quad p_y \quad p_z)^T$, and attitude matrix, ${}^{0}_{e}R = \begin{pmatrix} n_x & o_x & a_x \\ n_y & o_y & a_y \\ n_z & o_z & a_z \end{pmatrix}$, respectively[10].

For dual-manipulator coordination system, the subspace description of master manipulator can be expressed as[11],

$$ {}^{w}U = {}^{w}_{mb}H\,{}^{mb}U = \begin{pmatrix} {}^{w}_{mb}R & {}^{w}_{mb}T \\ 0 & 1 \end{pmatrix} {}^{mb}U \qquad (1) $$

Where ${}^{mb}U$ is base coordinate system of master manipulator, ${}^{w}U$ is world coordinate system, and the transformation relationship of ${}^{mb}U$ and ${}^{w}U$ is described as homogeneous transformation matrix ${}^{w}_{mb}H$; ${}^{w}_{mb}R \in R^{3\times3}$ is rotation matrix, and ${}^{w}_{mb}T \in R^{3\times1}$ is translation vector.

The essence of coordination calibration for dual-manipulator base coordinate is to obtain the solution of homogeneous transformation matrix ${}^{mb}_{sb}H$ as follows,

$$ {}^{mb}U = {}^{mb}_{sb}H\,{}^{sb}U = \begin{pmatrix} {}^{mb}_{sb}R & {}^{w}_{sb}T \\ 0 & 1 \end{pmatrix} {}^{sb}U \qquad (2) $$

Where ${}^{sb}U$ is base coordinate system of slave manipulator, ${}^{mb}_{sb}R \in R^{3\times3}$ is rotation matrix, ${}^{mb}_{sb}T \in R^{3\times1}$ is translation vector.

Assume that transformation relationship between master and slave manipulators as ${}^{mb}_{sb}H$, has been solved, and then kinematics equation as $f = f(q_i)$ for n-DOF manipulator can be obtained, where $q_i = (q_1, q_2, \cdots, q_n)^T$ means n-dimensional joint vector. Thus, under master-manipulator base coordinate system ${}^{mb}U$, the attitude expression of master-manipulator end effector is $f_m = f_m(q_i^m)\cdot{}^{me}_{mt}H$, where ${}^{me}_{mt}H$ means transformation relationship between the end-effector coordinate systems of master and salve manipulators. Similarly, under slave-manipulator base coordinate system ${}^{sb}U$, the attitude of slave-manipulator end effector can be expressed as $f_s = {}^{mb}_{sb}H \cdot f_m(q_i^m)\cdot{}^{se}_{st}H$.

The interrelationship of master-slave manipulator coordinate systems is shown as follows,

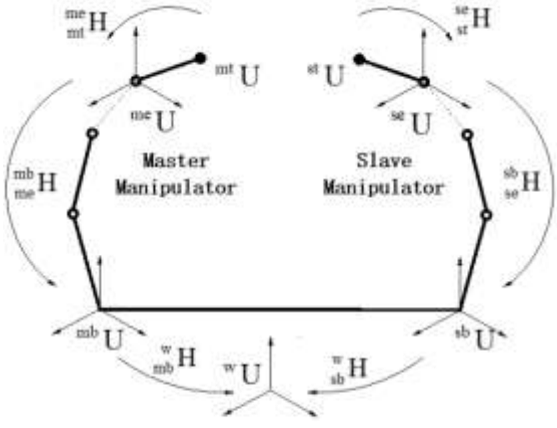

Figure2 Interrelationship schematic of dual-arm coordination system

2. Model predictive control algorithm

This paper presents a master-slave position coordination control method based on model predictive control algorithm, while position controller for slave manipulator can obtain real-time position correction from distance measuring sensors. Position feedback control loop can provide position correction towards tracking direction, to improve position-control precision and avoid random disturbance presented in position control system.

Model predictive control algorithm can be used to effectively handle optimization control of constrained objective for multi-variable system, which falls into three parts as steady-state mathematical model, steady-state target calculation and dynamic control[12]. Model predictive control algorithm, including motion predictive model, position feedback correction of manipulator end and rolling optimization for motion model, is applied for research in this paper, as shown in Figure3.

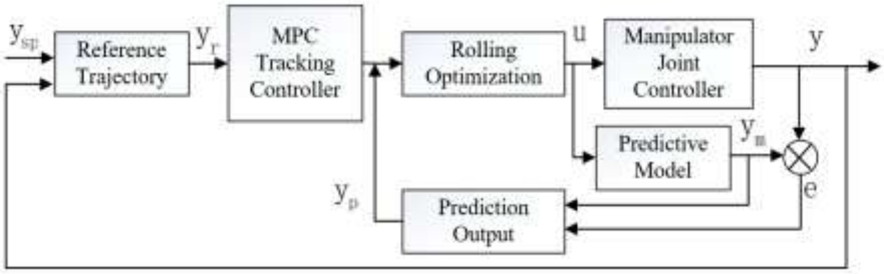

Figure3 MPC algorithm block diagram

2.1 Model predictive

According to kinematics model of manipulator, system state-space model is built to be discretization handled, then

$$\begin{cases} x(k+1) = A\cdot x(k) + B\cdot \Delta u(k) \\ y(k) = C\cdot x(k) \end{cases} \quad (3)$$

Where x(k) is location state of manipulator end, u(k) means input for manipulator end position, and y(k) is output of manipulator end position.

On the basis of dynamic matrix control theorem, the value of each sampling point for unit step response can be described as dynamic coefficient $a_i = \left[a_1 \dots a_m\right]$, where m means length of time domain for model. If there is input u(k-i) at some time k-i(k≥i), then under action of △u(k-i) output y(k) can be expressed as

$$y(k) = a_i \cdot \Delta u(k-i) \quad (4)$$

By linear superposition principle, if there is input at time k+j, then N step of predictive output for y(k+j) can be expressed as

$$\hat{y}(k+j) = \hat{y}_0(k+j) + \sum\nolimits_{i=1}^{j} a_i \cdot \Delta u(k+j-i) \text{, (j=1, 2, 3, …, N)} \quad (5)$$

From the equation above, if assume that the number of control increment is M, then at the time P, predictive output is

$$\hat{y}_{PM}(k) = \hat{y}_{P0}(k) + A\cdot \Delta u_M(k) \quad (6)$$

Where $\Delta u_M(k) = \begin{pmatrix} \Delta u_M(k) \\ \Delta u_M(k+1) \\ \vdots \\ \Delta u_M(k+M-1) \end{pmatrix}$, $\hat{y}_{PM}(k) = \begin{pmatrix} \hat{y}_M(k+1) \\ \hat{y}_M(k+2) \\ \vdots \\ \hat{y}_M(k+P) \end{pmatrix}$, $\hat{y}_{P0}(k) = \begin{pmatrix} \hat{y}_0(k+1) \\ \hat{y}_0(k+2) \\ \vdots \\ \hat{y}_0(k+P) \end{pmatrix}$, dynamic matrix $A = \begin{pmatrix} a_1 & 0 & \cdots & 0 \\ a_2 & a_1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ a_P & a_{P-1} & \cdots & a_{P+M-1} \end{pmatrix}$, P is prediction horizon, and M is control horizon.

2.2 Rolling optimization

For rolling optimization of multi-input and multi-output system, performance index need to be optimized in any period of executing task process, and time domain of optimization will step forward with time changing, then

$$\min I(k) = \left\| y_r(k) - \hat{y}_{PM}(k) \right\|_Q^2 + \left\| \Delta u_M(k) \right\|_R^2 \quad (7)$$

Where the first item on the right of equation is to optimize tracking performance of system towards reference trajectory, and the second one is to optimize stability performance of control increment for system with ability of completing target tasks; reference trajectory $y_r(k) = \begin{pmatrix} y_r(k+1) \\ y_r(k+2) \\ \vdots \\ y_r(k+P) \end{pmatrix}$, error weight

matrix $Q = diag\begin{bmatrix} Q_1 & Q_2 & \cdots & Q_P \end{bmatrix}$, control action weight matrix $R = diag\begin{bmatrix} R_1 & R_2 & \cdots & R_M \end{bmatrix}$.
When substituting into predictive model, then

$$\min I(k) = \left\| y_r(k) - \hat{y}_{P0}(k) - A \cdot \Delta u_M(k) \right\|_Q^2 + \left\| \Delta u_M(k) \right\|_R^2 \tag{8}$$

2.3 Feedback correction

Due to model errors, environmental changes and other unpredictable disturbances, there will exist considerable errors between predictive and actual position outputs, and thus real-time feedback needs to be applied to model correction.
Prediction error is defined as

$$e(k+1) = y(k+1) - \hat{y}_{PM}(k+1 \mid k) \tag{9}$$

Where y(k+1) is actual position output, $\hat{y}_{PM}(k+1 \mid k)$ is predictive position output.
After prediction error correction, then predictive position output is

$$\hat{y}_{cor}(k+1) = \hat{y}_{PM}(k) + h \cdot e(k+1) \tag{10}$$

Where $\hat{y}_{cor}(k+1) = \begin{pmatrix} \hat{y}_{cor}(k+1 \mid k+1) \\ \vdots \\ \hat{y}_{cor}(k+P \mid k+1) \end{pmatrix}$, and $\hat{y}_{cor}(k+1)$ is predictive output of system at the time of k+1 after correction, and $h = \left[h_1, \cdots, h_P\right]^T$ is error correction vector, $h_1 = 1$. With time changing, the predictive moment will change to the next, and correction value will be acted as initial value of prediction in next moment.

3. Experimental simulation and analysis of dual-manipulator coordination control

According to the built interrelationship of coordination kinematics model in section1.3, the Robotics Toolbox of MALAB platform can be used to build a 3D dual-manipulator model[13], and then make simulation and analysis for the master-slave position coordination control method based on model predictive control algorithm as shown in Figure4,

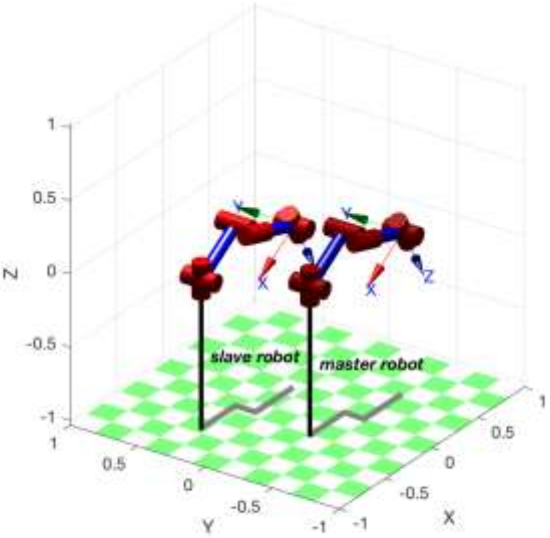

Figure4 Dual-arm simulation

According to the simulation experimental requirement of trajectory-tracking precision for slave manipulator towards the master end position, experimental parameters is set as follows:
Movement path for master manipulator end is from the origin of coordinate (0, 0 , 0) to X = sin(t*2π/2000) , Y = -0.8 ,Z = 0.8, which becomes the input of expected trajectory for slave manipulator. Then prediction tracking for the end of slave one is from coordinate origin towards expected trajectory, and experimental time for simulation is 2s and number of simulation points is set as 2000; Control horizon and prediction horizon for model prediction is M=50 and P=50, respectively. The simulation results are shown in the following figures.

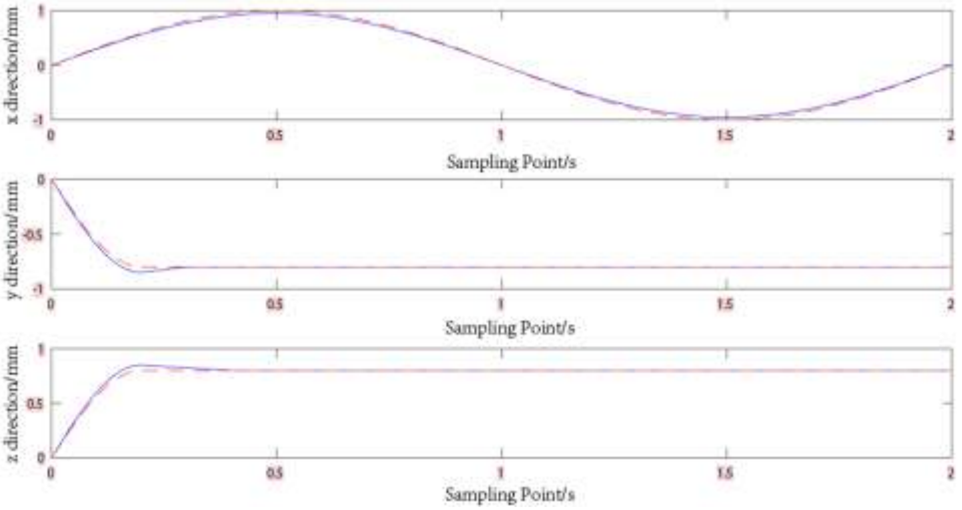

Figure5 Actual trajectory and predictive trajectory

Figure5 shows real-time tracking result towards expected trajectory in x, y, z directions of slave manipulator end based on model predictive control algorithm, where dotted line means predictive trajectory and solid line means actual tracking trajectory. Thus, the application of this algorithm for slave manipulator tracking expected trajectory could achieve ideal tracking effect quickly with just a little overshoot.

Figure6 shows the comparison result of traditional PID control algorithm and MPC algorithm, in which the actual tracking trajectory of PID and predictive trajectory of MPC are compared by 1000 sampling points in 1 second. Compared with traditional PID control algorithm, model predictive control algorithm for manipulator tracking can achieve ideal effect much faster and more stable.

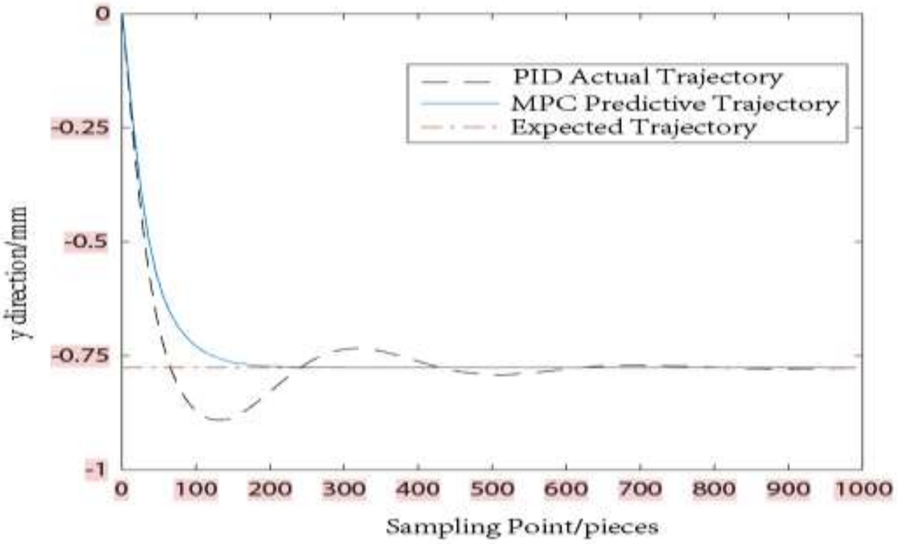

Figure6 Comparison graph of MPC predictive trajectory and PID actual trajectory tracking

Figure7 shows tracking trajectory error of this algorithm. Continuously plotted against time, the slope variation of expected trajectory along x-axial will lead to presence of slight fluctuation in trajectory error which will maintain within ±0.05. The expected trajectories along y- and z-axials are set as fixed value, where response curve can reach steady state rapidly with small overshoot, and simultaneously, trajectory error approaches zero gradually.

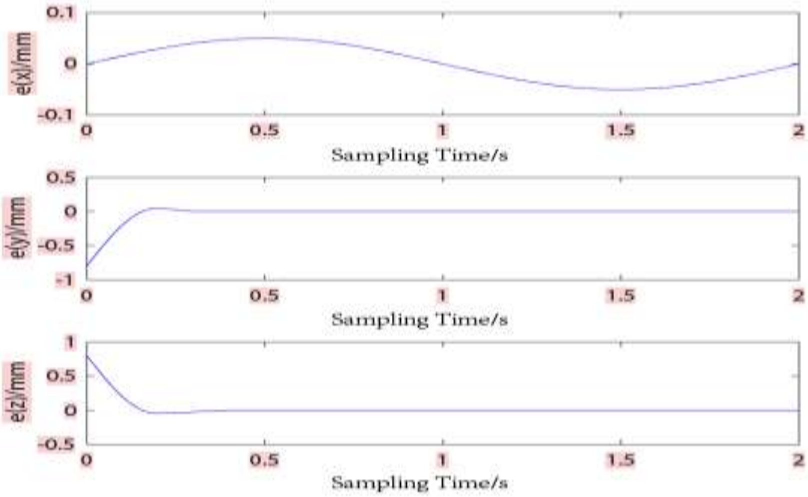

Figure7 MPC trajectory tacking error

Dynamic matrix control algorithm realizes trajectory tracking control for slave manipulator end towards master position. As shown in Figure5, 6 and 7, the simulation results show that accuracy tracking control for slave manipulator towards the reference trajectory from objective position of master manipulator end can be realized effectively.

II. CONCLUSION

This paper presents dual-manipulator master-slave coordination control algorithm based on model predictive control method, to solve accuracy problem of dual-manipulator welding control. The interrelationship of two manipulators is built from dual-manipulator kinematics model, and optimal input sequence for expected performance index can be solved according to manipulator kinematics analysis. Finally, model predictive control algorithm is applied as position-solution algorithm and optimal solution of manipulator joint motion is solved by kinematics analysis, the simulation results shows that predictive trajectory of manipulator end can achieve accurate and real-time tracking toward expected trajectory, to achieve ideal coordination welding performance.

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