Design of Control System for 6-DOF Manipulator

Xianglong Li¹, *, Zikun Quan²,³ and Dongping Liu³, b

¹School of Jinan, Qilu normal University, Jinan 250000, China;
²School of Weihai, Shandong University, Weihai 264200, China.
³CO., LTD of Shenzhen, SHENZHEN FENGPING A.I. CO.,LTD, Shenzhen 580000, China.

*Corresponding author e-mail: 858199882lxl@gmail.com, a 304916550@qq.com,
bliud@fengping.tech

Abstract. The manipulator is a complex system with high precision, high nonlinearity and strong coupling, the design of the manipulator control system has an important influence on the stable operation of the manipulator. The structural design, drive design and hardware design of the manipulator are the key contents of the manipulator, which needs to be coordinated and controlled as a whole. Through the establishment of a six-degree-of-freedom manipulator dynamics model, and the design of the manipulator control system is conducted in this paper.

Keywords: control system; manipulator; six-degree-of-freedom.

1. Introduction
The research on the six-degree-of-freedom (6-DOF) manipulator control system is mainly to make the manipulators complete the specified motions in accordance with the established requirements of the people; which require planning the motion trajectory of the manipulators, then the position control is used in each joint axis to drive the manipulator to achieve the desired moving target, and the selection of control algorithm is a key step to ensure the smoothness and accuracy of the manipulator. The selection design of control algorithm generally requires a kinematic model based on the manipulator system, in addition, it should consider both the simplicity of the system control and the motion state of the system, a 6-DOF manipulator dynamics model is established in this paper, based on this, the design and research of the manipulator control system is carried out.

2. Technology Development of 6-DOF Manipulator

2.1. Research status of 6-DOF manipulator control system
The 6-DOF manipulator is usually controlled by many motors in coordination, in order to achieve effective communication among different motors, it is necessary to establish the data communication system between the main controller and each motion control unit, at present, the commonly used control system architecture includes the central type and distributed type. The central system architecture is a relatively traditional control method, which can meet the control requirements of most systems, but when the central controller fails, it will have a serious impact on the whole control system. Moreover,
due to the complexity of the central system architecture, it is difficult to maintain in the later stage. The distributed control system is a microprocessor that distributes control signals to each control node, under this control system, the main controller only needs to implement the functions of bus connection and manipulator kinematics algorithm, which can simplify the input of control equipment and improve the control stability of the whole system.

2.2. Research status of trajectory planning of 6-DOF manipulator
The trajectory planning of the 6-DOF manipulator is the basis for ensuring the accurate motion and stable control of the manipulator, it is conducive to improve the motion efficiency of the manipulator and improve the tracking error of the system. Under normal conditions, performance optimization indicators are used to describe the trajectory planning performance of manipulator. The research on the manipulator trajectory planning algorithm with time optimization is mature, according to the different trajectory planning; it can be divided into the optimal time motion trajectory algorithm along the pre-set path and the point-to-point processing algorithm under the optimal time. The optimal time motion trajectory algorithm along the pre-set path considers the position, velocity, acceleration and second-order acceleration of the manipulator, the trajectory curve that meets the requirements can be obtained by a high-order polynomial curve connecting the key points in the joint space of the manipulator. The point-to-point processing algorithm under optimal time is mainly to abstract multiple working points in space, and requires the manipulator joints to move at each working point to complete the pre-set task, the motion of each joint is linear and independent and need to have a stay time at the working point, the current common method is to use polynomial interpolation among nodes to conduct trajectory planning.

3. Algorithm Design of 6-DOF Manipulator Control System

3.1. Establishment of kinematics model of 6-DOF manipulator
As shown in Fig.1, the mechanical structure of 6-DOF manipulator belongs to 3D open-loop chain structure, which is composed of a base and a rotating arm from top to bottom, these parts are connected by six rotating joints, by controlling these six parts, the full position of the manipulator in the workspace can be achieved.

![Fig. 1 manipulator model](image-url)
In this paper, the coordinate system is established for the six rotating joints in accordance with the right-hand rule and the D-H principle, according to the spatial geometric relationship among the two adjacent members of manipulator, the positive kinematics equation of the 6-DOF manipulator can be established, the relationship between joint coordinates and mechanical end position can be accurately reflected, but the inverse kinematics mode is more common in practical applications. According to the inverse kinematics model, the manipulator controller can calculate the angle value that each joint needs to reach when completing the ideal motion trajectory, the control system of the manipulator is realized by setting the position of the shutdown. After the selection of the manipulator configuration, the kinematic parameters need to be determined, according to the mechanical arm configuration of Fig.1, the reference coordinate system and joint coordinate system of the manipulator are established according to the manipulator configuration of Fig.1, as shown in Fig.2, because the coordinate system has offsets a1 and a2, therefore, the 1, 2, and 3 coordinate system does not coincide with x-axis, and the spatial relationship of x1, x2, and x3 is shown in Fig.3.
The kinematic parameters of the 6-DOF manipulator should include the angle of rotation $\theta$ around the $z$-axis, the distance $d$ between two adjacent common perpendiculars on the $z$-axis, the length of common perpendicular, and the included angle $\alpha$ between two adjacent $z$-axes. In this paper, the motion parameters are determined by the D-H rule, the homogeneous equation is used to describe the spatial geometric relationship of each connecting rod of the manipulator with respect to the reference coordinate system, the $4 \times 4$ homogeneous matrix is used to describe the geometric relationship between adjacent connecting rod, then the end position of the manipulator relative to the reference coordinate system can be derived, the D-H parameters of the manipulator in this design are shown in Table 1.

| two adjacent coordinate systems | $\theta$ | $d$ | $a$ | $\alpha$ |
|-------------------------------|---------|-----|-----|---------|
| 0 - 1                         | 01      | 0   | a1  | 90°     |
| 1 - 2                         | 02      | 0   | a2  | 0       |
| 2 - 3                         | 03      | 0   | a3  | 0       |
| 3 - 4                         | 04      | $-d_4$ | a4  | 90°     |
| 4 - 5                         | 05      | $d_5$ | 0   | 90°     |
| 5 - 6                         | 06      | 0   | 0   | 0       |

3.2. Design of motion planning algorithm for 6-DOF manipulator

Trajectory planning is an important task in the motion control of manipulators; different motion modes require different trajectory planning algorithms, specifying the appropriate trajectory curve is one of the simplest trajectory specification algorithms, however, this single-type trajectory planning algorithm cannot meet the rigid and flexible impact during the movement of the manipulator, in the subsequent development process, a synthetic trajectory planning curve is designed according to the characteristics of various planning curves, this trajectory planning algorithm usually uses the form of a piecewise function, and the inflection point value of each curve of the function needs to meet the continuity of the motion state parameters. The control algorithm of motion modes of Trial Mode is adopted in this paper, which concentrations the traditional Auto Mode and Teach Mode motion modes; it not only makes the system to move along the established trajectory, but also ensures that the system can be controlled in real time in this process. The motion mode of Trial Mode selects the split trapezoidal velocity profile during the design process and requires segmentation planning during each sampling period. In addition, the interpolation algorithm should also specify the trajectory constraints.

3.3. Debugging design of motion planning algorithm of 6-DOF manipulator

After the design of 6-DOF manipulator control algorithm is completed, before the experimental platform of manipulator is built, the manipulator algorithm debugging software needs to be written, and the algorithm function is solved and verified to ensure the feasibility of the algorithm function and the accuracy of the control logic. In this paper, the manipulator control system is built on the WinCE system platform, C++ language is used to write algorithm code to run within the controller, the MFC framework is used in the selection of software framework, a reasonable program framework is designed, its functions need to include mechanical parameters, tool parameters, operating parameters and coordinate system parameters, and can guarantee the simulation verification of different motion modes.

4. Hardware System Design of 6-DOF Manipulator

In the design process of the manipulator, considering the electromechanical coupling relationship of the system, the design process is divided into two parts: mechanical structure design and control system design, in the hardware design process, it is necessary to firstly fit the basic technical parameters of the manipulator to screen components, and then based on the calculation of the shutdown torque, select the motor that meets the power requirements.
(1) Selection of manipulator configuration

In order to ensure that the manipulator can complete the desired motion requirements in the working space, the object can be grasped to the exact position and the posture movement can be conducted, it is necessary to make the manipulator meet the condition of freedom. The configuration selection of manipulator is the basis of the design of the manipulator, the higher the degree of freedom, the higher the flexibility of the manipulator, but the control structure is also more complicated. Therefore, the freedom of the manipulator should be matched with the task, in this paper, a manipulator with six rotating joints is designed based on the six-degrees-of-freedom kinematics model, in order to make the manipulator have a closed solution, it is necessary to make the adjacent three joint axes intersect at one point, therefore, the positioning structure selects a connecting rod with 0° or 90° rotation angle, and the six joints of the manipulator are driven by six torque motors, respectively.

(2) Selection of drive motor of manipulator

There are many kinds of drive motors for the joints of the manipulator; this design selects a DC brush motor with simple configuration and convenient control. In addition, in order to meet the different types of motion of manipulator, it is also necessary to take into account the maximum load torque of the motor and the maximum angular velocity of each joint, under normal circumstances, peak control power at locked-rotor is an important reference indicator in the motor selection process. The dynamic parameter requirements of each joint are the basis for selecting the joint drive components and transmission components; static and dynamic methods can be used to calculate the dynamic parameters of the manipulator, the static method is to ignore the dynamic influence of the load and only calculate the static load; the dynamic method is to design the static load and the dynamic load simultaneously in the calculation process. Assume that the centre of the joint theory node carries the joint focus, and the centre of the connecting rod carries the weight of the connecting rod, and then the required torque of each joint can be calculated.

(3) Selection of manipulator controller

DSP TMS320LF2407 is used as the main control chip in this design, which has 40MHz clock frequency and rich on-chip resources, its built-in event manager module can meet the control requirements of the drive motor, in addition, the chip with small size can save the space of board. In order to improve the dynamic control performance of the system, a double closed-loop control method including a position loop and a speed loop is adopted, the controller can input the expected control scheme of the manipulator in the industrial personal computer, and the controller calculates the ideal trajectory planning curve by algorithm calculation, and converted to the number of pulses of the incremental code disk. The deviation between the actual pulse number and the ideal pulse number is used as the input of the joint controller; the integral separation PID controller solves the position control amount of the system, which can be reflected as the different duty cycle of the PWM waveform, thereby ensuring that the motor driver controls the motor operation.

5. Software System Design of 6-DOF manipulator

(1) PID control algorithm

DSP TMS320LF2407 is the main control chip, the speed loop and the position loop use integral separation PID control; in addition, in order to ensure the control stability of the system, it is necessary to debug the control law of the system according to the actual operating environment. When determining the absolute position of the motor, manipulator effectively combines the signal output of the zero-position hall proximity switch and the incremental encoder Z-channel. The PID control method has the advantages of simple principle, convenient use, strong applicability and strong robustness, the relationship between the input e(t) output u(t) of the PID controller is:

\[ u(t) = K_p e(t) + K_i \int_{0}^{1} e(t)dt + K_d \frac{de(t)}{dt} \]

Among them, the function of the proportional adjustment parameter Kp is to adjust the system to reduce the overshoot, moreover, it can control the adjustment speed, but when the parameter is too large,
the stability of the system is lowered. The action of the integral adjustment parameter KI is on the elimination of the steady-state error, as long as the error has integral adjustment, it continues until the system reaches the error state. The differential adjustment parameter KD can reflect the change of the system deviation and realize the advanced control of the system, which is beneficial to improve the dynamic performance of the system.

(2) Communication software design

In the control process, the manipulator not only needs to communicate with the six lower computer, but also needs to interact with the I/O board to realize the control of the propulsion device and the hydraulic device, CAN communication is required in these parts, the data frame type and standard frame format are adopted in the CAN communication network, the data transmitted by the upper computer includes the expected angle of each joint, the desired speed, the heavy torque received by each joint, the PID parameter, the I/O control amount, etc., and the accepted data mainly includes the combined angle of each axis of the current manipulator, the current position of the propulsion device and the value of the displacement sensor. The lower computer does not communicate with each other, and the lower computer interacts with the upper computer, therefore, the upper computer can coordinate and manage the seven lower computers by using point-to-point communication mode, the upper computer is the active mode, and the lower computer is the slave mode, only when the lower computer receives the frame data or instruction sent by the upper computer, the data will be returned accordingly.

6. Conclusion

The manipulator is a tool that is widely used in modern industry and it is important for ensuring the stability of industrial production. In this design scheme, according to the motion characteristics of the manipulator in the working space, a 6-DOF manipulator with chain joint structure is designed, and by estimating the torque of each joint, the selection of the motor required by the manipulator is achieved. In system modelling, the integral separation PID control method is used to adjust the state performance of the system, achieve improvement in system response speed, overshoot and steady state performance.

References

[1] Zhang Jinjing, Cui Tao, Pei Dong, Wang Quanzhou, Lu Yan. Design and Implementation of 4-DOF Manipulator Control System Based on FPGA [J], Journal of Machine Design, 2017, 34(7), pp.62-66.
[2] Zhang Xiaoying, Li Dewei, Xi Yugeng, Chen Weidong. Design of Constrained Predictive Control System for 6 Degrees-of-freedom Manipulators [J], Control Theory & Applications, 2014, 31(11), p.1464-1472.
[3] Zhong Jun, Cao Jianshu. Implementation of 6-DOF Robot Arm Control System Based on Kinect V2.0 [J], Machine Tool & Hydraulics, 2018, 46(9), pp.81-85.
[4] Bu Ziling, Yang Ruhan, Peng Yue. System Design of Wireless Controlled six-degree of Freedom Manipulator based on Arduino, [J], China Computer & Communication, 2017, (7), pp.90-93, 97.
[5] Wang Hao, Fan Pingqing, Wang Yansong, Li Cong. Research on Precise Control of Robot Arm Based on ROS Platform, Light Industry Machinery, 2018, 36(6), pp.42-47.