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Design of Programmable High-Cost-Performance Gantry-Type Loading and Unloading Manipulator

Lijie Zhou [1, 2, *], Chunlin Cai [1, 2], Ruilin Hao [1, 2]

[1] Department of Mechanical Engineering, Hebei University of Water Resources and Electric Engineering, Cangzhou Hebei, 061001, China

[2] Hebei Industrial Manipulator Control and Reliability Technology Innovation Center, Cangzhou Hebei, 061001, China

* Corresponding author: Lijie Zhou (Email: zhoulijie@hbwe.edu.cn)

ABSTRACT

To meet the demand for low-cost, highly reliable, and easily programmable loading and unloading equipment in automated CNC machining production lines, this paper designs a three-axis gantry-type loading and unloading manipulator. The whole machine adopts a gantry frame and a Cartesian coordinate structure, with stepper motors and synchronous belts as the transmission scheme, and is equipped with a pneumatic clamping end effector to realize the automatic transfer of workpieces between machine tools and silos. The control system is built with a PLC, stepper motor drivers and a touch screen, supporting touch screen programming, point-to-point motion, signal input and output control, delay control and other functions. The human-machine interaction system adopts a touch screen for visual operation, reducing the threshold of debugging and use. Through lightweight structural design, modular component design and simplified programming design, on the premise of ensuring a repeated positioning accuracy of ±0.1 mm and stable and reliable operation, the overall cost and deployment cycle of the machine are significantly reduced. Prototype tests show that the manipulator meets the requirements of flexible processing for small and medium batch production and has high engineering application value.

KEYWORDS

Gantry Manipulator; Loading and Unloading; Programmable Control; PLC.

1. INTRODUCTION

With the rapid popularization of intelligent manufacturing and flexible processing technologies, automatic loading and unloading of CNC machine tools has become a key link to improve production efficiency, reduce labor costs and ensure processing consistency, and is also one of the core supports for the transformation of the manufacturing industry towards automation and intelligence[1]. Gantry-type manipulators are widely used in CNC machining scenarios such as turning[2], milling[3] and grinding[4] due to their advantages of simple structure, good rigidity, small space occupation, convenient maintenance and adaptability to single-machine automation transformation, making them the preferred equipment for small and medium-sized manufacturing enterprises to realize automation upgrading.

From the perspective of the international development status, developed countries represented by the United States, Japan and Germany have formed a mature industrial system in the field of gantry-type loading and unloading manipulators[5]. Their products feature high positioning accuracy, strong operational stability and high intelligence. For example, gantry manipulators from enterprises such as FANUC of the United States[6], KUKA of Germany[7] and Yaskawa of Japan[8] can realize multi-axis coordinated control and complex trajectory planning. However, such equipment has problems such as high initial investment, expensive operation and maintenance costs, closed core technologies and long customization cycles[9], which make it difficult to adapt to the budget and deployment needs of small and medium-sized manufacturing enterprises. In addition, the complex programming logic[10] places high professional skill requirements on on-site operators, further increasing the application threshold for small and medium-sized enterprises[11].

In view of the above industry pain points of loading and unloading manipulators, this paper takes programmable, high cost performance and easy deployment as the core design objectives, completes the design of mechanical structure, control system and human-machine interaction system, optimizes component selection and structural layout, and minimizes the cost on the premise of ensuring equipment performance. Compared with similar products, the manipulator designed in this paper has stronger programmability and operational convenience, and can be debugged and deployed without professional programming skills, providing a more adaptable automatic loading and unloading technical solution for small and medium-sized manufacturing enterprises.

2. MECHANICAL STRUCTURE DESIGN OF THE MANIPULATOR

2.1. Overall Structural Scheme.

The gantry-type loading and unloading manipulator designed in this paper adopts a three-axis Cartesian coordinate structure with an overall gantry frame layout, which is mainly composed of a gantry frame, a mobile sliding table, a transmission system and an end clamping mechanism. The schematic diagram of its overall structure is shown in Figure 1.

The X-axis realizes long-stroke movement in the horizontal direction along the gantry beam, responsible for covering the horizontal distance between the machine tool and the silo; the Y-axis moves longitudinally along the beam to achieve precise positioning of the workpiece within the horizontal range; the Z-axis realizes lifting movement in the vertical direction to complete the picking and placing of the workpiece; the end clamping mechanism is driven by pneumatic power to realize reliable clamping of workpieces of different specifications. The vertical columns of the whole machine are fixed on the ground or beside the machine tool, and the beam span is flexibly designed according to the layout of CNC machine tools and silos, which can adapt to the synchronous loading and unloading requirements of one CNC machine tool with a compact structure and high space utilization rate.

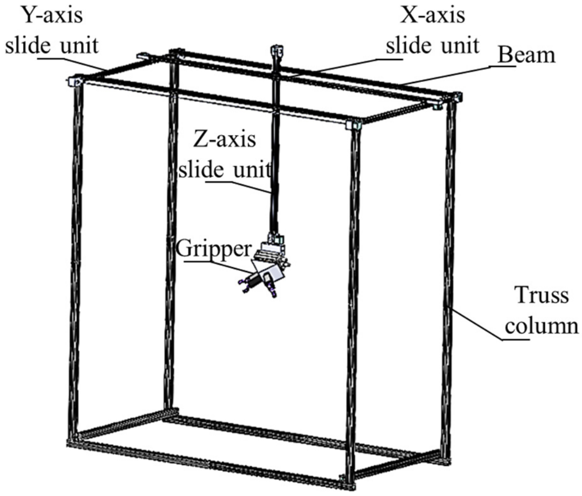

Fig 1. Schematic diagram of the overall structure of the manipulator

2.2. Mechanical Structure Design of Motion Axes.

The frame and beam are the core components to ensure the rigidity and motion stability of the manipulator, which need to balance rigidity, lightweight and cost control[12]. In this design, a combined structure of high-strength aluminum profiles is adopted and assembled by bolt connection. Through static check and finite element analysis, it is ensured that the deformation of the beam and column is less than 0.05 mm under high-speed movement and rated load of the manipulator, meeting the positioning accuracy requirements. The selection of aluminum profiles effectively reduces the overall weight of the machine, reduces the load of the drive system, and at the same time cuts down the material and processing costs, reducing the weight by more than 30% compared with the all-steel structure. The selection of the transmission system directly affects the motion accuracy, speed and cost of the manipulator. Combined with the motion requirements of the manipulator, a synchronous belt transmission scheme is adopted, which has the advantages of high transmission efficiency, strong load capacity and low cost, and can meet the requirements of high-speed movement. Closed-loop stepper motors are selected as the drive devices for each axis. Stepper motors have the characteristics of low response cost, high positioning accuracy and easy construction. Stepper motors with different power ranges can be selected according to the load and speed requirements of each axis, and matched with corresponding types of stepper motor drivers to realize closed-loop position control.

In terms of mechanical structure design, the X-axis is an extremely critical motion axis, and both strength and accuracy must be considered in its design[13]. The X-axis adopts 2040 aluminum profiles to build the main frame, and the mechanical structure of the X-axis is shown in Figure 2.

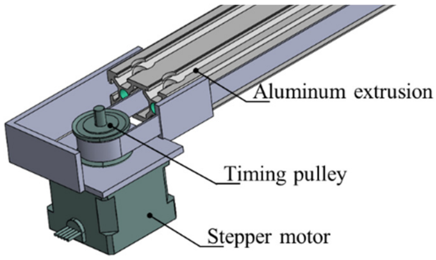

Fig 2. Schematic diagram of the overall structure of the manipulator

In the design of the Y-axis, considering the requirements of the overall structural balance and stiffness of the manipulator, a dual Y-axis design scheme is introduced, and 2040 aluminum profiles are selected to construct the main part of the Y-axis. The transmission system adopts a synchronous belt transmission mode and is equipped with two aluminum profile pulleys. The two parallel Y-axes realize transmission through a transmission shaft and are driven by a single stepper motor. The structure and transmission system of the Y-axis are shown in Figure 3.

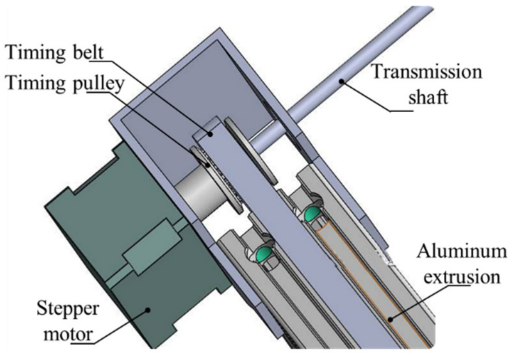

Fig 3. Structural design drawing of the manipulator's Y-axis

The Z-axis is a motion axis in the vertical direction, and 2040 aluminum profiles are selected to build its main frame. The matched aluminum profile pulleys are fixed on the X-axis, and this installation method enables the Z-axis to move smoothly along the X-axis direction. The structure and transmission system of the Z-axis are shown in Figure 4.

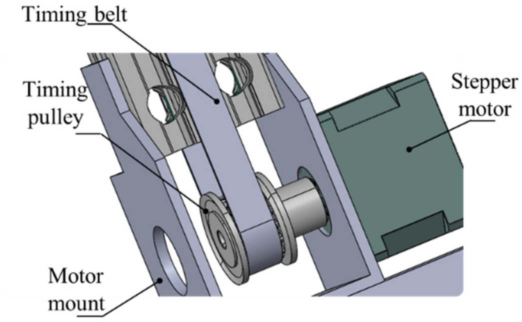

Fig 4. Structural design drawing of the manipulator's Z-axis

In this paper, the Simulation finite element analysis module built in SolidWorks is used to carry out static performance analysis on the overall structure of the robot. With the 3D modeling function of SolidWorks, the core structural models such as the robot's column, beam and transmission components are accurately constructed. In the Simulation module, the overall structure is simplified. Considering that the main stress point of the manipulator is at the middle position of the X-axis beam, other structures such as columns are simplified in the simplification process. The fixed points are set at the bottom of the Y-axes on both sides, and the loading point is selected at the middle position of the X-axis beam. According to the typical working condition of the robot's full-load handling, a composite load of 150N including gravity, inertia force, friction force and impact force generated during material grasping is accurately applied, and the boundary constraint conditions are set in combination with the actual installation method. The intelligent mesh generation technology is used to divide the model into fine and reasonable tetrahedral meshes to ensure the calculation accuracy, and then the deformation displacement distribution nephogram is generated, as shown in Figure 5.

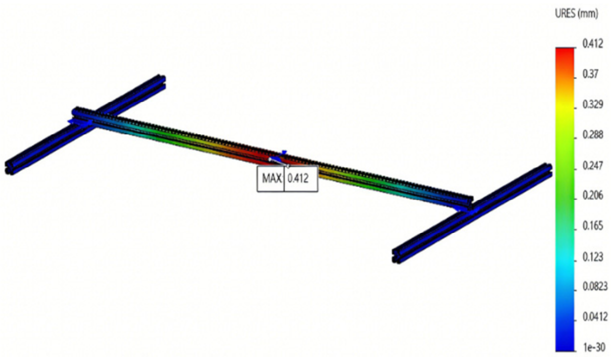

Fig 5. Deformation nephogram of static analysis of the manipulator's main structure

The results show that the maximum deformation of the key load-bearing components is controlled at 0.4 mm, which is far lower than the 1 mm threshold required by the technical specification. The analysis results verify the reliability and safety of the manipulator in terms of mechanical performance, and provide scientific and strong technical support for the stable operation of the material handling robot.

To verify the rationality and practicability of the mechanical structure design, the manipulator prototype is fabricated based on the aforementioned design scheme, following the processes of component processing, assembly, debugging and performance testing, with strict control over processing and assembly accuracy. The physical prototype and test scene are shown in Figure 6.

Fig 6. Physical drawing of the manipulator prototype

3. CONTROL SYSTEM DESIGN OF THE MANIPULATOR

3.1. Composition Architecture of the Control System.

Combined with the programmable requirements and high cost performance objectives of the manipulator, the control system adopts a PLC as the main controller, stepper motors and stepper motor drivers as the motion execution components, and an industrial touch screen as the human-machine interaction component. The composition block diagram of the control system is shown in Figure 7. This architecture has the advantages of flexible logic control, convenient expansion, strong stability and moderate cost, and can meet the automatic control needs of small and medium-sized manufacturing enterprises.

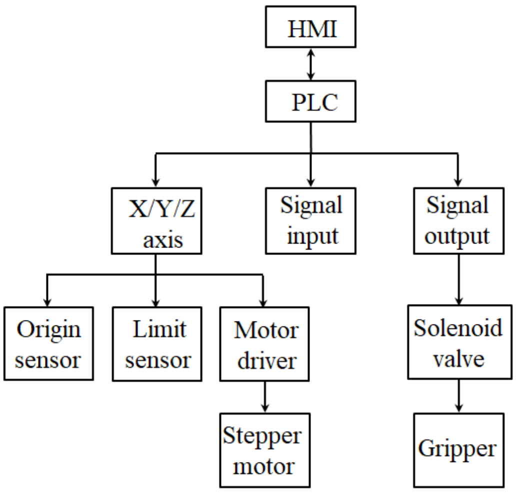

Fig 7. Composition block diagram of the control system

Among them, the lower computer PLC serves as the core control unit, responsible for processing the motion logic of the manipulator, multi-axis coordinated control, I/O signal acquisition and processing, safety interlock control and other functions. It receives operation instructions from the HMI and detection signals from sensors, and sends motion control instructions to the stepper motor drivers to realize the automatic operation and manual operation of the manipulator; the servo system receives control instructions from the PLC, drives the stepper motors to complete precise position and speed control, and realizes the synchronous motion and positioning of each axis; the detection unit includes limit switches, origin switches, emergency stop buttons, etc., which are used to collect the operating status of the manipulator and workpiece information, providing a basis for the control logic of the PLC; the industrial touch screen is used to realize visual operation, including parameter setting, status monitoring, program editing, manual control and other functions, reducing the operation threshold for operators.

3.2. Software Design and Motion Control.

The control process of the manipulator is divided into manual mode and automatic mode, with the automatic mode as the main operating mode, and its working flow is shown in Figure 8. After the system is powered on, the manipulator first performs the homing operation, and each axis moves to the preset origin position to complete initialization. Then the PLC receives the machining completion signal of the CNC machine tool and judges whether the loading and unloading conditions are met; if the conditions are met, the Z-axis descends, the end pneumatic gripper closes to clamp the workpiece, and after the clamping in-position sensor sends a signal, the Z-axis ascends, and the X-axis and Y-axis move coordinately to transfer the workpiece to the clamping position of the CNC machine tool; after the Z-axis descends and the gripper releases to complete loading, the PLC sends a signal to the CNC machine tool to start machining; after the CNC machine tool completes machining, it sends a signal, and the manipulator repeats the above actions to take out the finished workpiece and transfer it to the finished product area of the silo, completing a loading and unloading cycle; the PLC judges whether the preset number of cycles is reached, if not, the cycle continues, and if reached, it stops running and sends a prompt signal. The manual mode is mainly used for equipment debugging and fault handling. Operators can control the jog movement of each axis and the opening and closing of the gripper through the manual operation interface of the HMI, realizing single action debugging such as homing, workpiece picking and placing, which is convenient for equipment debugging and maintenance.

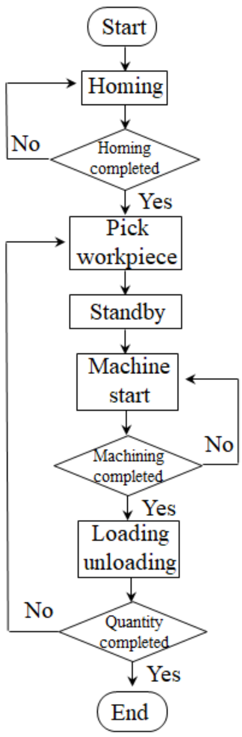

Fig 8. Working flow chart of the control system

The motion control of the manipulator adopts the point-to-point control mode. The motion speed and position coordinates of each axis can be set through the HMI with a speed adjustment range of 10~500 mm/s and a repeated positioning accuracy of ±0.1 mm, meeting the accuracy requirements of CNC machining loading and unloading. The PLC sends pulse signals to the servo drivers through the high-speed pulse output interface to control the rotation angle and speed of the stepper motors, ensuring the precise positioning of the X-axis, Y-axis and Z-axis. At the same time, the system supports the program editing function. Operators can set the motion path and action steps of the manipulator through teach programming or manual input of program instructions, realizing flexible loading and unloading of various types of workpieces. I/O allocation is a bridge for establishing communication between the PLC and external equipment, which directly affects the expandability of the manipulator. On the one hand, it is necessary to plan interfaces for the manipulator itself, and on the other hand, it is also necessary to design extended specification interfaces for the manipulator and external equipment. The I/O allocation of the manipulator is shown in Table 1.

Table 1. Manipulator I/O Allocation Table

Type	Address	Description
Input	I0.2	X-axis origin limit sensor
Input	I0.5	Y-axis origin limit sensor
Input	I1.0	Z-axis origin limit sensor
Input	I1.1	Main start button
Output	Q0.0	X-axis pulse output
Output	Q0.1	Y-axis pulse output
Output	Q0.2	X-axis direction
Output	Q0.3	Z-axis pulse output
Output	Q0.7	Y-axis direction
Output	Q1.1	Z-axis direction
Output	Q1.1	Gripper A clamp/release
Output	Q1.2	Gripper B clamp/release
Output	Q1.3	Gripper switching

4. HUMAN-MACHINE INTERACTION SYSTEM DESIGN OF THE MANIPULATOR

An economical industrial touch screen TK6072 is selected as the HMI hardware, with a 7-inch screen and a resolution of 800×480, supporting touch operation. The built-in Ethernet interface can realize real-time communication with the PLC, which can not only clearly display the operating status and various parameters of the manipulator, but also quickly receive operation instructions from operators. The touch screen is installed in an embedded way and fixed on the control box of the manipulator at a position convenient for operators to observe and operate. Core buttons such as manual/automatic switching, start/pause and emergency stop are set on the interface, allowing operators to quickly switch the operating mode and control the operation of the whole machine.

The manual operation interface is mainly used for equipment debugging. The interface is equipped with jog control buttons for each axis, corresponding to the movement operations of X-axis left/right, Y-axis forward/backward and Z-axis up/down. With speed adjustment, the motion speed of each axis can be flexibly controlled. At the same time, gripper opening and closing buttons are set to facilitate operators to manually complete single action debugging. The parameter setting interface can realize online modification and saving of various parameters, including motion parameters and cycle parameters. The motion parameters include speed and position coordinates, and the process parameters include delay time and I/O operation. The processing requirements of workpieces of different specifications can be adapted through parameter adjustment. The program editing interface supports manual programming, through which operators can directly set the action process, and set the motion path and action steps. All programs can be saved and modified. The main interface of the human-machine interaction system is shown in Figure 9, and the manual control interface is shown in Figure 10.

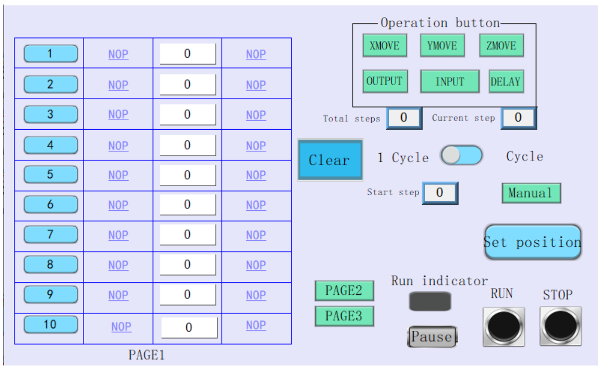

Fig 9. Main interface of the human-machine interaction system

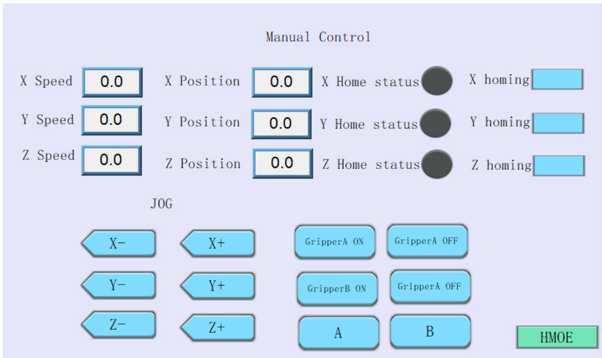

Fig 10. Manual control interface of the human-machine interaction system

5. SUMMARY

Focusing on the demand for automatic loading and unloading in CNC machining, this paper completes the overall design of a programmable high-cost-performance gantry-type loading and unloading manipulator, realizes the integrated research and development of the mechanical structure, control system and human-machine interaction system, and effectively solves the current industry pain points of high cost, poor versatility and complex operation of loading and unloading equipment. At the same time, it makes up for the shortcomings of insufficient programmability of domestic similar products and high cost and inconvenient deployment of foreign similar products. In terms of mechanical structure, a three-axis Cartesian coordinate structure is adopted, the transmission scheme is optimized, and high-cost-performance components and lightweight materials are selected. On the premise of ensuring repeated positioning accuracy and stable and reliable operation, the structural compactness and cost reduction are realized, and the overall cost is significantly lower than that of articulated robots of the same specification; the control system is composed of PLC, drivers, stepper motors and HMI, realizing programmable motion control of the manipulator and balancing control performance and cost; the human-machine interaction system adopts an industrial touch screen for visual operation, designs a simple and intuitive operation interface, supports teach programming, reduces the operation threshold for operators, and adapts to the flexible production needs of multiple varieties and small batches. Prototype tests show that the manipulator runs stably and reliably with accurate positioning, can realize the automatic transfer of workpieces between machine tools and silos, meets the process requirements of CNC machining loading and unloading, has a short deployment cycle and low maintenance cost, is suitable for the automation upgrading and transformation of small and medium-sized manufacturing enterprises, and has good versatility and engineering application value.

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