Research on intelligent tracking positioning robot with drilling and screwing function

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Abstract. The container manufacturing industry is a typical labor-intensive industry in China, its manufacturing technology urgently needs to be automated with the demographic dividend disappearing. According to the technical requirements and space limitation for automatic locking screws between the wood floors and container steel girders, and based on the application of dynamical simulation technology, EtherCAT bus servo control technology, multisensory information fusion technology and other technologies, our team has developed an intelligent robot, which meets the automatic drilling and screwing process for dry containers. The robot has up to 49 servo motors, and through the data fusion of torque, position and image etc., the robot can move and locate by itself, and automatic deal with the exceptional situations of tool wear, floating lock, not drilled through and etc., and realizes the flexible production of multi-axis drilling and screwing. The robot can generate processing data reports, making container digital manufacturing further.

1. Introduction

Container transportation is an important mode of transportation widely used in the world. At present, container production enterprises are mainly concentrated in Southeast Asia, and China produces more than 80\% of the global containers [1]. However, in terms of container manufacturing technology, China’s container manufacturing is still dominated by manual operation with poor production environment and low efficiency. To meet the production requirements of high efficiency and low resources in modern manufacturing industry, container manufacturing is gradually realizing semi automation and automation.

For the manufacturing of dry cargo containers, one process is to lock the wooden floor on the container chassis with screws. The number of locking nails for a 53 feet special container (53BST) is up to 1462, and this process mainly depends on manual operation until now. Therefore, enterprises urgently need to realize the automation of this process. Although the full-automatic screw locking machine has been widely used in the automatic assembly of electronic industry, electrical industry and automobile industry, the screw locking process in the container industry still stays at the manual operation level, due to the large size of the container, the open operation environment and the drilling and screw locking of high-strength steel.
At present, our research team has developed an intelligent tracking positioning robot with drilling and screw locking function, which has achieved satisfactory experimental results. Facing the current technological innovation of digital manufacturing and intelligent manufacturing, this work then analyzes some technical points of this robot from the perspectives of mechanical structure, industrial Ethernet control and neural network model.

2. Mechanical structure scheme design

452 screws are required for a 45 feet container, and 1462 screws for a 53 feet special container, the screw distribution of 45 feet container is shown in Fig. 1. In the container industry, in a container production line, there are 6-8 stations for drilling and screw locking, and the process arrangement is as follows: manual marking, drilling, cleaning, screw scattering, screw locking, cleaning, inspection and repairment, as shown in Fig. 2. The wood floor fastening processing needs more than 60 employees in a production line, it is obvious that the screw locking is a labor-intensive work for the container production.

![Fig. 1. The screw position distribution of the 45 feet container (The cross star represents the screw).](image1)

According to the position distribution and fastening process of container floor screw, the function modules of the robot can be divided into vehicle platform, drilling and reaming device, cleaning device, screw sorting and feeding device, screw locking device, transposition device of drilling and screwing, quality testing device, etc., as shown in Figure. 3.

![Fig. 2. The container drilling and locking process: (a) outside lineation, (b) inner lineation, (c) drilling, (d) cleaning, (e) screw locking.](image2)

The overall mechanical structure scheme is as follows: the car is a cuboid frame structure; and two rows of drilling and locking modules are suspended under the upper frame, one module includes 11 drilling units and 11 locking units, the position switching between the drilling units and locking unites is realized by the ball screw servo mechanism, which is in the middle of upper frame; the screw sorting supply device and the electrical cabinet are placed on the upper frame, the sorted screws will be transported to the screw clamping mouth of each locking unit under the control signal; two servo traveling driving wheels is set on one side of the underframe, and the driving direction of the robot can be adjusted through the differential speed of the two servo drive wheels; each drill-lock unit is equipped with a blowout device to blow cuttings to one side; the robot is equipped with a vision system, which can locate according to the edge position of the wood floor, and the vision system can
also detect and value the quality of the drilling and screw locking. The overall design is shown in Fig. 4.

Fig. 3. The structure of the robot

Fig. 4. Overall 3D design effect

The working process of the machine is as follows: 1) under the joint positioning of vision and laser, guide the robot into the container and confirm the position of the bottom beam; 2) after drilling, blow air for cleaning; 3) move the lock units to the drill position and feed the screws at the same time; 4) after the screw locking, reset the position of drill and lock by the position transposition device; 5) make the robot back a distance, and the visual system detects the quality; 6) generate and upload the report, 7) continue the next cycle.

3. Control scheme design

3.1. Control scheme based on industrial Ethernet

According to the design scheme shown in Fig. 4, the required standard components such as servo motor, cylinder, magnetic valve, and sensors are shown in Table 1. The number of servo motor is up to 49, and more than 300 IO ports are required to associate with solenoid valves, sensors, etc. In the industrial application environment, PLC is a very popular controller, but the ordinary pulse PLC controller can only drive several servo motors, and the bus PLC controller becomes the preferred. At the same time, considering the data communication requirements of real-time remote monitoring, we have established a real-time Ethernet framework.

At the same time, considering the real-time data communication requirements of remote monitoring, there should be established a real-time Ethernet framework to realize the remote control of the robot.

There are many real-time industrial Ethernet protocols in the world. According to different real-time and cost requirements, different principles are used, which can be roughly divided into the following three categories:
1) It is completely based on TCP \ UDP \ IP, the hardware layer has not been changed, and the traditional Ethernet controller is adopted, typically including standard Ethernet /IP and Modbus TCP;

2) Some are based on TCP \ UDP \ IP, the hardware layer has not been changed, and has process data protocol, which is directly transmitted by Ethernet frame. TCP / UDP still exists, but it is controlled by timing layer, typical of which are PROFINET RT and Powerlink;

3) The industrial Ethernet realized by modifying the Ethernet protocol realizes hard real-time with response time less than 1ms. The slave station uses specific hardware and uses real-time Ethernet controller, typical of which are PROFINET IRT, CC-Link IE, SERCOS III and Ethernet.

Tab. 1. Component List

| No | Component name        | Quantity | No | Component name        | Quantity |
|----|-----------------------|----------|----|-----------------------|----------|
| 1  | Wheel motor           | 2        | 7  | Cylinder              | 73       |
| 2  | Drill motor           | 22       | 8  | Solenoid valve        | 81       |
| 3  | Screwing motor        | 22       | 9  | Magnistor             | 146      |
| 4  | Transposition motor   | 2        | 10 | Optoelectronic switch | 9        |
| 5  | Scan detecting motor  | 1        | 11 | Near-switch           | 22       |
| 6  | Laser sensor          | 4        | 12 |                       |          |
|    | Total                 |          |    | Total                 | 331      |

Fig. 5. Ethernet control framework

At present, EtherCAT, as the fastest-growing fieldbus system, has been highly praised by customers because of its fast, accurate and strong expansibility. Moreover, it has been more and more widely used because of its complete openness, flexible topology and technological update keeping pace with the times [2, 3]. Therefore, the project adopts EtherCAT bus as the communication mode of servo motion control. Correspondingly, the EtherCAT bus PLC adopts Omron NJ5001, which can control 64 servo axes. The control framework of the robot is shown in Fig. 5.

The EtherCAT port of the master NJ is connected in series with all slave EtherCAT servo drivers. The Dimetix laser sensor (dae-10-050) with EtherCAT communication module is used. All EtherCAT slave units set the node number in Sysmac Studio software. HMI and remote IO module (Omron EIC202) realize Ethernet / IP communication with NJ station through the switch. The camera and video recorder are set in the same network segment, and remote data transmission is also realized through the switch.
3.2. Neural network algorithm

In the actual drilling and screw locking process, tool wear is inevitable, as shown in figures 6 and 7. The robot has 44-axis in the drilling and locking process, it is difficult to rely on human eyes to identify which drill bits and screwdriver bits are seriously worn and need to be replaced in time. Therefore, it is necessary to independently identify and judge the abnormal conditions of tools through the trained neural network algorithm [4].

There are many kinds of neural networks, among them, the BP neural network algorithm is widely used in the fields of function approximation, pattern recognition, prediction and control because of its strong adaptability, certain fault tolerance and generalization ability. BP neural network is a multi-layer feedforward neural network trained according to the error back propagation algorithm. Its network topology is composed of input layer, hidden layer and output layer. The neurons in each layer form a full interconnection through weight coefficient and threshold, and use the gradient descent method to continuously adjust the weight coefficient and threshold to minimize the error between the network output value and the expected value. Its powerful nonlinear mapping ability enables it to approach any continuous function with any accuracy in theory [5, 6]. Therefore, this network is selected to establish the tool wear prediction model in this paper.

There are too many kinds of tool wear, including adhesive wear, abrasive wear, fatigue wear and so on, and the tool wear is a nonlinear process, and there are too many influencing factors. In production, workers are most concerned about how to confirm the tool should be changed, to make this judgment, workers need to accumulate a lot of experience.

For the judgment of tool wear, the most direct intuitive way: the depth of drilling or screw locking, the torque, and the completion using time. According to the actual engineering application, this project constructs a three-level network to confirm whether the tool is replaced or not. Take depth, torque and using time as the input layer, through these three input parameters, it can independently identify the non penetration / floating lock, broken tool / screw loose, and tool wear degree (hidden layer), and...
deduce the tool OK or NG (output layer) from the hidden layer. The neural network structure of the project is shown in Fig. 8.

\[
\begin{align*}
    a_1^{(2)} &= g(a_0^{(1)} \cdot w_{1,1}^{(1)} + a_2^{(1)} \cdot w_{1,2}^{(1)} + a_3^{(1)} \cdot w_{1,3}^{(1)}) \\
    a_2^{(2)} &= g(a_0^{(1)} \cdot w_{2,1}^{(1)} + a_2^{(1)} \cdot w_{2,2}^{(1)} + a_3^{(1)} \cdot w_{2,3}^{(1)}) \\
    a_3^{(2)} &= g(a_0^{(1)} \cdot w_{3,1}^{(1)} + a_2^{(1)} \cdot w_{3,2}^{(1)} + a_3^{(1)} \cdot w_{3,3}^{(1)}) \\
    a_1^{(3)} &= \sigma(a_1^{(2)} \cdot w_{1,1}^{(2)} + a_2^{(2)} \cdot w_{1,2}^{(2)} + a_3^{(2)} \cdot w_{1,3}^{(2)}) \\
    a_2^{(3)} &= \sigma(a_1^{(2)} \cdot w_{2,1}^{(2)} + a_2^{(2)} \cdot w_{2,2}^{(2)} + a_3^{(2)} \cdot w_{2,3}^{(2)})
\end{align*}
\]

According to the structure shown in Fig. 8, equations (1) to (5) can be established, and the parameter value of matrix \( w \) can be learned and determined through the process shown in Fig. 9. The work on this area is still in study.

![Neural network parameter calculation flow](image)

**Fig. 9. Neural network parameter calculation flow**

**4. Experiment and Test**

At present, through a large number of experiments and tests, the robot can achieve the technical indicators shown in Table 2, and the quality of the drilling and screwing can meet the product standards of containers. Fig. 10 shows the appearance of the robot, Fig. 11 is the real testing scenario, and Fig. 12 is the scenario after drilling and screw locking test.

| No  | Technical content                  | Technical index   |
|-----|-----------------------------------|-------------------|
| 1   | Number of simultaneous boreholes  | 22                |
| 2   | Number of locking pins at a time  | 22                |
| 3   | Average drilling efficiency       | \( \leq 5\)s/row |
| 4   | Average screwing efficiency       | \( \leq 5\)s/row |
| 5   | Average moving speed of vehicle platform | \( \geq 0.3\)m/s |
| 6   | Vehicle positioning accuracy     | \( \leq 2.5\)mm  |
| 7   | Efficiency increase              | \( \geq 30\)%    |

At the same time, many problems have been found through experiments and tests:
1) When drilling, there is a lot of vibration in the modules, which has a great influence on the broken tool and tool wear, but it is difficult to quantify.
2) The weight of the whole vehicle reaches more than 4 tons. When walking in the container, the container board will tilt up and the bottom beam will be bent and deformed;
3) When the car is walking, the current sound of the servo motor of the driving wheel is very loud.

5. Conclusion
At present, the robot is still being tested and optimized. This paper introduces the mechanical structure and workflow of the designed robot, the communication control mode based on Real-time Ethernet, and establishes the tool wear neural network algorithm model based on engineering application elements, and the successfully trained model can enable the robot to independently identify the tool wear condition. The robot has realized multi axis servo flexible control through EtherCAT bus. In addition, the use of RJ45 interface greatly simplifies the electrical wiring. Through Ethernet / IP communication, NJ controller can upload the processing data of Fieldbus to SCADA (Supervisory Control And Data Acquisition) and ERP (Enterprise Resource Planning), and provide data flow for the digital manufacturing of containers.

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References
[1] Shipping Transactions Bulletin, (2021)China's container industry and multimodal transport development report. http://www.ship.sh/news_detail.php?nid=43010
[2] Hu, K, Xue L, Chen, Q. (2019) Multi-axis motion control network based on real-time Ethernet. Transducer and Microsystem Technologies, 38:42-48
[3] Wu, G., Su, F., Li, X., Zou, W., & Chen, J.. (2013) Real-time ethernet based on passive optical networks. Optical Engineering, 52(2), 5007.
[4] Yin, F., Mao, H., Lin, H., & Gu, Z.. (2012) Back propagation neural network based calculation model for predicting wear of fine-blanking die during its whole lifetime. Computational Materials Science, 59:140-151.
[5] Zhao, J., Liu, H., Hu, J. (2018). (2020) Experimental Study on Wear Monitoring of Ultrasound Vibration Drilling Bit Based on BP Neural Network. Machine Design and Research, 36(2): 83-86.
[6] Abu-Mahfouz, I.. (2003) Drilling wear detection and classification using vibration signals and artificial neural network. International Journal of Machine Tools and Manufacture, 43(7): 707-720.