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Research and Design of an Automatic Grasping Manipulator for Screw Surface Defect Detection Based on PLC

Zhu Zhenglong*, Yang Guangyao, Ye Zhenhuan, Zhang Nanqing, Zhang Qiang, Yang Zexi

College of Engineering, Zunyi Normal University, Zunyi, Guizhou 563006

Correspondence to: Zhu Zhenglong

Abstract: This paper studies and designs an automatic grasping manipulator for screw surface defect detection. The mechanical claw, lifting arm, pushing arm, and base are analyzed in terms of force conditions. Three-dimensional models of each structure and the overall system are designed. Furthermore, the PLC control circuit diagram and human-machine interaction interface are developed. The designed automatic grasping manipulator can reduce missed inspections, lower labor intensity and human resource costs, and improve detection efficiency.

Keywords : Grasping manipulator; Design calculation; PLC

1 INTRODUCTION

Currently, most defect inspections in screw manufacturing enterprises are performed manually. Due to the variety of defects such as scratches, bumps, and surface color abnormalities, manual inspection is prone to missed detections. Additionally, manual inspection suffers from high costs and low efficiency, with missed defects often leading to significant economic losses such as batch returns. To address these issues, many enterprises have introduced grasping manipulators and related automated equipment [1].

In response to the above challenges, this paper designs a PLC-controlled manipulator equipped with a lightweight designed gripper capable of accurately grasping eight small screws at once. This enables the automated batch handling of screws, thereby supporting the automated batch detection of screws to achieve efficient mass automated inspection[2].

2 OVERALL DESIGN CONCEPT OF THE AUTOMATIC GRIPPING MANIPULATOR

The automatic screw-gripping manipulator designed in this study aims to achieve efficient batch detection, requiring full automation of the entire process.The manipulator primarily consists of four degrees of freedom: rotation, lifting, telescoping, and clamping. Small-scale stepper motors are employed to drive the clamping and releasing actions of the mechanical claw, as well as the rotation of the base. Cylinders are used to drive the lifting of the large arm and the telescoping of the small arm, enabling the gripping, positioning, and placement of screws. This prepares the screws for surface quality inspection at the next station, ensuring strong versatility and flexibility.

3 STRUCTURAL DESIGN CALCULATION OF AN AUTOMATIC SCREW GRASPING MANIPULATOR

3.1 DESIGN CALCULATION OF THE GRASPING CLAW

The clamping force applied by the fingers on the screw must generally overcome the frictional force generated by gravity at the contact point between the screw and the fingers, which constitutes the static load. Since the motion of the workpiece involves inertial forces, dynamic loads should also be considered. However, given that the load in this design is relatively small, dynamic loads are not taken into account. Only the friction force in the vertical direction overcoming the gravity of the screw is considered.

The weight of a single screw is known to be 0.0375 kg, and each grasping operation handles 8 screws. Thus, the total mass of the screws is $m = 0.3$ kg. The fingers are made of Nylon PA6 material, and the static friction coefficient between Nylon PA6 and steel (screw) typically ranges from 0.2 to 0.4. For this design,

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the friction coefficient between the screw and the mechanical claw is taken as μ = 0.30. The gravitational acceleration is g = 9.8 N/kg, and a safety factor of 1.5 is adopted. The calculation process for the finger clamping force is as follows.

$$2uN = kmg, N = \frac{kmg}{2u} \quad (1)$$

$$N = \frac{1.5 \times 0.3 \times 9.8}{2 \times 0.3} = 7.35N \quad (2)$$

In the formula, N represents the finger clamping force, u denotes the friction coefficient between the screw and the gripper, k is the safety factor, m indicates the maximum mass of the screw being grasped, and g stands for the gravitational acceleration.

3.2 *Calculation Of Motor Torque For The Mechanical Claw*

The fingers of the mechanical claw can be simplified as a linkage mechanism, as shown in Figure 3-1. When the motor drives the sector gear to rotate, the frame-connected link 1 rotates clockwise in the direction indicated in Figure 2. Link 3 is subjected to force F_1 from link 1, which is the driving force generated by the motor via the sector gear. The screw exerts force N on link 3. The horizontal component of force F_1 and force N achieve moment balance about point O.

The lengths of l_1 and l_2 are known to be 0.09 m and 0.03 m, respectively. As derived earlier, N=7.35 N. According to the formula, when other values remain constant, a larger angle α results in a smaller driving force from the sector gear. Therefore, the driving force is at its maximum when angle α is at its minimum. The minimum value of α is known to be 30°.

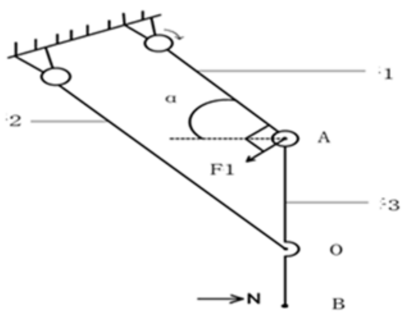

Figure 2 Force Analysis of the Mechanical Claw

Driving force of the sector gear:

$$F_1 sin\alpha l_1 - Nl_2 = 0, F_1 = \frac{Nl_2}{sin\alpha l_1} \quad (3)$$

$$F_1 = \frac{7.35 \times 0.03}{0.5 \times 0.09} = 4.90N \quad (4)$$

In the formula, F_1 represents the driving force exerted by the motor on the sector gear, N denotes the finger clamping force, l_1 and l_2 indicate the distances from point A to point O and point B to point O, respectively; given that the length of Link 1 is 0.1 m, the torque required for the motor to drive the sector gear is calculated as follows.

$$T = F_1 r = 4.90 \times 0.10 = 0.49Nm \quad (5)$$

If the gripper drive motor rotates at 50 degrees per second, its rotational speed is 10 r/min. The required power for the gripper drive motor is calculated as follows.

$$P = T \times \frac{2\pi n}{60} = 0.49 \times \frac{2 \times 3.14 \times 3000}{60} = 0.5w \quad (6)$$

3.3 *Design Calculation Of The Forearm Of The Grasping Manipulator*

The process of forearm extension is analyzed and calculated in three stages: acceleration, uniform motion, and deceleration, with reference to the Mechanical Design Handbook Sixth Edition: Pneumatic Transmission[3]. The standard operating speed range for pneumatic cylinders is 50–500 mm/s. The uniform motion speed of the forearm is 0.1 m/s, which falls within the reasonable range [2]. Given an acceleration time of 3 s, the acceleration of the forearm is calculated as follows.

$$a = \frac{\Delta v}{\Delta t} = \frac{0.1}{3} = 0.033\, m/s^2 \quad (7)$$

The load on the forearm consists of the mass of the gripper, the gripper drive motor, and the screws, which are 1.4kg, 1.2kg, and 0.3kg, respectively. The calculated acceleration is $a=0.033m/s^2$.The inertial force of the forearm is calculated as follows.

$$m = 1.4 + 1.2 + 0.3 = 2.90kg \quad (8)$$

$$F_1 = ma = 2.90 \times 0.033 \approx 0.10N \quad (9)$$

Considering the friction of the piston, etc., the static friction coefficient of the piston is typically 0.1~0.2, and the friction coefficient of the piston is taken as k=0.2, with g=9.8 N/kg.Static friction force of the forearm.

$$F_m = kmg = 0.2 \times 2.90 \times 9.8 \approx 5.68N \quad (10)$$

Thrust required for the forearm cylinder.

$$F_0 = F_1 + F_m = 0.10N + 5.68 = 5.78N \quad (11)$$

3.4 *Calculation Of The Required Thrust For The Main Arm Cylinder Of The Grasping Manipulator*

The main arm moves vertically in a lifting motion. The following analysis focuses on the upward movement driven by the main arm cylinder, which is divided into three phases: acceleration, uniform motion, and deceleration. With reference to the Mechanical Design Handbook Sixth Edition: Pneumatic Transmission[6], the standard operating speed range for pneumatic cylinders is typically 50–500 mm/s. The uniform motion speed of the main arm is 0.1 m/s (100 mm/s), which falls within the reasonable range [6]. The acceleration time is set to 2s.The acceleration of the main arm is calculated as follows:

$$a = \frac{\Delta v}{\Delta t} = \frac{0.1}{2} = 0.05\, m/s^2 \quad (12)$$

The load on the upper arm includes the manipulator, the motor driving the manipulator, screws, the forearm, and the forearm cylinder, with masses of 1.4 kg, 1.2 kg, 0.3 kg, 1.6 kg, and 0.3

kg respectively, and g = 9.8 N/kg. The inertial force and load on the upper arm are as shown below.

$$m = 1.4 + 1.2 + 0.3 + 1.6 + 0.3 = 4.80kg \quad (13)$$

$$F_1 = ma = 4.80\text{kg} \times 0.05\, m/s^2 \approx 0.21N \quad (14)$$

$$G = {}_{\text{mg}} = 4.80\text{N} \times \frac{9.8\text{N}}{\text{kg}} = 47.04N \quad (15)$$

Considering the friction of the piston, etc., the staticfriction coefficient of the piston is typically 0.1 to 0.3. Here, the friction coefficient k is taken as 0.2, and g = 9.8 N/kg. As shown in Figure 3,

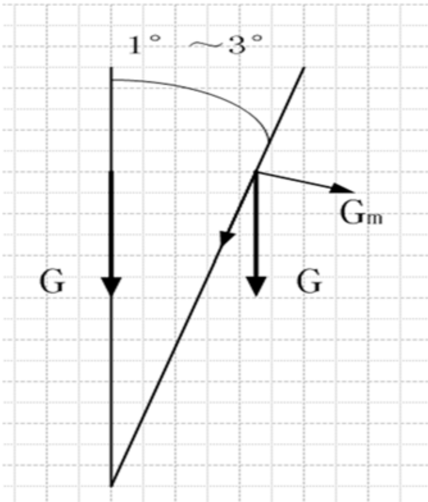

FIGURE 3 INCLINATION ANGLE OF THE UPPER ARM CYLINDER

if the lifting arm is installed completely vertical, the theoretical friction force is zero. However, in actual operation, this cannot be achieved, so a tilt angle of 1° to 3° is set. Therefore, gravity G has a component force G_m on the upper arm surface, which exerts a normal force on the side of the upper arm, resulting in a friction force F_m. The friction force of the upper arm and the thrust required by the upper arm cylinder are shown below.

$$G_m = G \times sin\,3^\circ = 47.04 \times sin\,3^\circ \approx 2.46N \quad (16)$$

$$F_m = G_m \times k = 2.46 \times 0.2 = 0.492N \quad (17)$$

$$G_q = G + F_m + F_1 = 47.742N \quad (18)$$

3.5 *TORQUE CALCULATION FOR THE GRIPPER MECHANISM BASE*

The load on the base shaft consists of the manipulator, the motor driving the manipulator, screws, the forearm, the forearm cylinder, the upper arm, and the upper arm cylinder, with masses of 1.4 kg, 1.2 kg, 0.3 kg, 1.6 kg, 0.3 kg, 1.8 kg, and 0.6 kg, respectively, and g = 9.8 N/kg.

Referring to the Concise Mechanical Design Handbook, the friction coefficient for thrust ball bearings is K_0 = 0.003 [25].Referring to the Concise Mechanical Design Handbook, the efficiency of ball bearings under thin oil lubrication is η_2 = 0.99, and the recommended transmission efficiency for a single-stage cylindrical gear accelerator is 0.97–0.98. Here, the gear transmission efficiency is taken as 0.97 [25].Referring to the Mechanical Design Course Design, the recommended transmission ratio for a single-stage cylindrical gear transmission is 3–5 [7]. Here, i = 3 is selected. The rotational radius of the shaft is 50 mm, i.e., R_0 = 0.05 m.

The calculation of the base load and the torque required for the base motor to overcome static friction is as follows.

$$\text{M0} = 1.4 + 1.2 + 0.3 + 1.6 + 0.3 + 1.8 + 0.6 = 7.2\text{kg} \quad (15)$$

$$\text{G0} = \text{M0g} = 7.2 \times 9.8 = 70.56\text{N} \quad (19)$$

$$T_0 = \frac{k_0 G_0 R_0}{\eta_1 \eta_2 i_1} = \frac{0.003 \times 70.56 \times 0.05}{0.97 \times 0.99 \times 3} = 0.004\text{Nm} \quad (20)$$

T_0 =In the formula, T_0 represents the torque load on the rotating shaft, K_0 denotes the friction coefficient of the thrust ball bearing, G_0 indicates the load on the shaft, R_0 signifies the rotational radius of the shaft, η_1 refers to the transmission efficiency of the gear, η_2 represents the transmission efficiency of the bearing, and i_1 stands for the transmission ratio of the single-stage gear reducer.

3.6 *BASE MOTOR POWER CALCULATION*

The rated speed of the preliminarily selected base motor is 10 r/min. The required power for the base motor is calculated as follows。

$$P = T \times \frac{2\pi n}{60} = 0.004 \times \frac{2 \times 3.14 \times 10}{60} = 0.004w \quad (21)$$

4 STRUCTURAL MODEL DESIGN OF THE GRIPPING MANIPULATOR

4.1 *MECHANICAL CLAW*

The mechanical claw is primarily responsible for gripping and releasing screws, which is critical to the success of the grasping operation. This design employs a double-rocker type gripper, which can provide appropriate clamping force to ensure stable workpiece handling, along with a simple structure, light weight, and compact size. The gripper of this robot utilizes a motor to drive a pair of identical sector gears. The driving sector gear and the driven sector gear respectively actuate the linkage mechanism to achieve synchronous opening and closing of the fingers. The meshing transmission of the gears offers high-precision gripping functionality. For the meshing sector gears (driving sector gear and driven sector gear), their motions are mutually constrained. The rotation of the driving sector gear drives the rotation of the driven sector gear. Therefore, although there are two sector gears, there is only one independent motion between them, namely the rotation of the driving sector gear.

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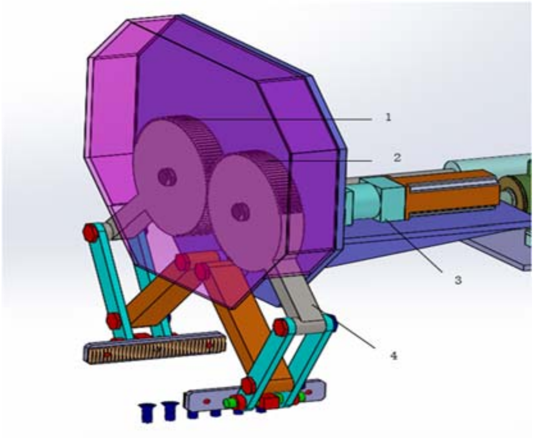
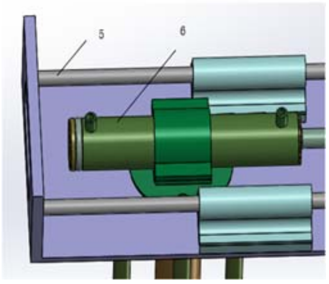


FIGURE 4 MECHANICAL CLAW

1 - Driven sector gear;2 - Driving sector gear;3 - Drive motor;4 - Mechanical claw.

4.2 *EXTENSION, RETRACTION, AND LIFTING FUNCTIONS*

The extension, retraction, and lifting functions form the foundation for ensuring the manipulator's flexibility in adapting to different working heights and positions. These functions allow the manipulator to move vertically (up and down) and horizontally (extending and retracting laterally). In this design, the robotic arm performs linear reciprocating motion. Both the forearm and the main arm utilize single-piston rod double-acting cylinders to achieve the extension and retraction functions, offering a cost-effective solution with high performance. The specific structures are illustrated in Figure5 and Figure 6.



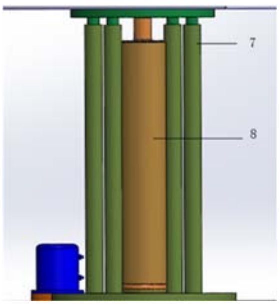


FIGURE 5 FOREARM **FIGURE 6 MAIN ARM**

5-Forearm Guide Rod， 6-Forearm Cylinder， 7-Main Arm Guide Rod， 8 - Main Arm Cylinder

4.3 *BASE DESIGN*

The base is primarily used for the rotation of the entire manipulator. In this design, the base employs a motor-driven single-stage cylindrical gear reducer to drive the rotation of a vertically installed shaft. To withstand axial loads, thrust ball bearings are mounted on the shaft. The specific structure is shown in Figure 7.

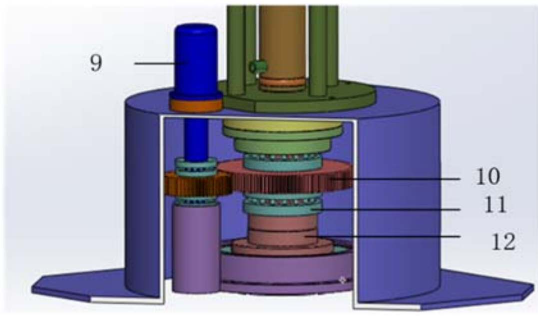


FIGURE 7 BASE

9-Base drive motor;10-Single-stage cylindrical gear reducer;11-Thrust ball bearing;12-Base shaft.

4.4 *OVERALL STRUCTURAL DESIGN OF THE AUTOMATIC SCREW GRASPING MANIPULATOR*

The overall structural design is illustrated in Figure 8. It consists of a mechanical gripper, a transversely driven forearm, a vertically moving main arm, and a base. During the grasping process, the base and the mechanical gripper work together to determine the grasping position. The rotation of the base enables continuous screw grasping, while the transverse cylinder and forearm are primarily used for positional adjustments.

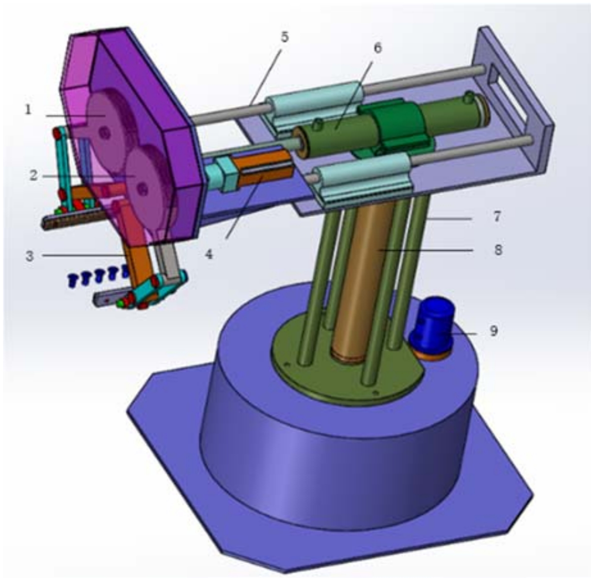


FIGURE 8 OVERALL DIAGRAM OF THE MANIPULATOR

1-Driven Sector Gear; 2-Driving Sector Gear; 3-Drive Motor;4-Mechanical Gripper;5- Forearm Guide Rod;6-Forearm

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Cylinder;7-Main Arm Guide Rod; 8-Main Arm Cylinder; 9-Base Drive Motor.

4.5 *Determination Of Mass Parameters For The Manipulator*

Referring to the Concise Mechanical Design Handbook, the material assigned after modeling is Nylon PA6. This material offers excellent wear resistance, high impact resistance, and fatigue resistance, making it suitable for frequently moving components (such as gears and bearings). Its density is approximately 1.1–1.2 g/cm³, which is significantly lower than that of metals. Furthermore, weight can be further reduced through thin-walled design techniques [25]. With moderate costs, it is well-suited for the lightweight design of small manipulators. Using the mass properties function in SolidWorks software, the preliminary masses of the various parts of the manipulator are summarized in Table 1. The mass of the screw for gripping refers to GB/T 5782-00, where a single M8 bolt has a mass of 0.037 kg The design requires gripping 8 screws at a time, and the total mass is rounded up, resulting in a maximum load of 0.3 kg for screw gripping.

Table 1 Mass Parameters of the Manipulator and Load

Claw kg	Forearm kg	UpperArm kg	MaximumLoad kg
1.4	1.6	1.8	0.3

5 Design Of The PLC Control Circuit For The Screw Gripping Manipulator

This paper selects the S7-1200 DC/DC/DC PLC as the controller. Its built-in RJ45 Ethernet port (PN) connects to the PROFINET bus to control the Leadshine L7PN400P drive, which in turn controls the servo motors for the base and the mechanical claw. The forearm and upper arm cylinders are controlled via 3-position, 4-way solenoid valves. The HMI is connected through the PROFINET bus.An external power supply is distributed through the circuit breaker QF to supply the drives, solenoid valves, and the PLC. After the drives pass the power-on self-test, the PLC sends commands via PROFINET to drive the servo motors. Simultaneously, it controls the solenoid valves through the DO module to switch the pneumatic circuits, actuating the upper arm and forearm cylinders. The motor operational status is monitored in real time through feedback signals. The system includes protection mechanisms against overload and overvoltage. In case of a drive fault, the output is automatically cut off and feedback is sent to the PLC, ensuring electrical safety and coordinated operation of mechanical components. The designed control circuit diagram is shown in Fig 9.

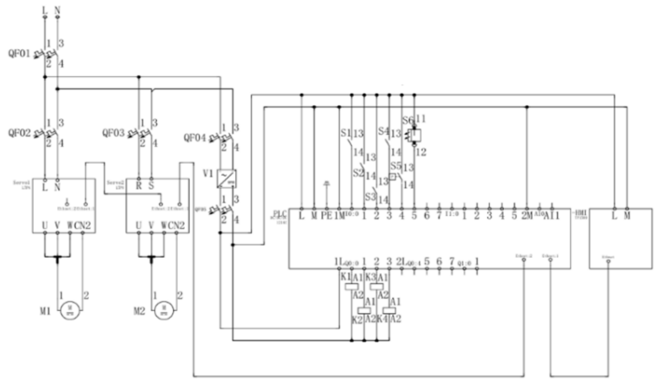

Figure 9 PLC Control Circuit Diagram

6 Conclusion

This paper designed an automated screw grasping manipulator system, including force calculations for each component and structural design. Additionally, the PLC control circuit diagram and human-machine interface were developed. The system significantly reduces missed inspections, lowers manual labor intensity, and improves production efficiency.

Fundings

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