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Design and analysis of 3-DOF cylindrical-coordinate-based manipulator

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ABSTRACT

The joint-type six-degrees-of-freedom (6-DOF) manipulator fulfills many complex motion and industrial operations, but does not need so much freedom in many practical situations. For example, the mechanical arm operations of stamped work-piece feeding and the automatic process of picking and placing work-pieces on the conveyor belt only require three translational degrees of freedom. In this study, the principle of the cylindrical coordinate mechanism is used to design a mechanical arm with one revolute pair and two prismatic pairs, meeting the low-cost, small volume, and specificity requirements of practical applications. This article analyzes the size-synthesis problem of the 3-DOF mechanism and optimum design of the cylindrical coordinate mechanism according to various constraint conditions. The direct and inverse kinematics equations of the manipulator are established, and the dynamic equations of the manipulator are derived using Lagrangian methods. Using the minimum weight principle of mechanical design, this paper discusses a modular design method and the optimum structural design of the manipulator, and applies a design scheme for an elastic spherical pair to compensate for the displacement and deflection errors between the motor driving shaft and the slider motion along the guide. The structural strength and stiffness are calculated using the finite element method. Through the application of a planar machine-vision system, the profile of the work-piece can be identified and positional coordinates located synchronously during the robot manipulations. The kinematic calibration method of the manipulator system is studied using a genetic algorithm, and the mathematical calibration equations are established. Experimental studies on the mechanical reliability, positional accuracy, and calibration application of a mechanical arm prototype are carried out. The experimental results show that the selected stepper motor has sufficient driving ability in the process of manipulating the work-piece, and the repeated positioning errors after the calibration satisfy the design requirements of the manipulator.

1. Introduction

Small powder-metallurgic parts have the characteristics of being simple to manufacture and suitable for mass production. Such parts are widely used in automobiles, electric tools and other applications; work-pieces such as small-modulus gears and irregular-shape parts are very suitable for powder metallurgy. However, after the working procedures of extrusion and sintering, these shaped parts will suffer a degree of thermal deformation, and a metal mold must be applied to meet the requirements of dimensional tolerance, contour tolerance, and surface roughness. The current refinement process is almost entirely manual, as shown in Fig. 1, where the operator takes the part out of the packet tray, places it into the mouth of the lower die, checks the correct position of the part by visual inspection, and then presses the push-button switch to turn the punch machine on. When the upper die moves up to the stop position, the part that has been reshaped is pulled out of the mouth of the lower die. The operator faces considerable risk during this operation. When one hand is in the mouth of the die, if the on button is accidentally depressed by the other, the operator's fingers will be badly hurt by the punching upper die. The refinement of powder-metallurgic parts is not only laborious but also tiring. This makes the risk of serious injuries reasonably high, and accidents have occurred in many enterprises. Therefore, the design a manipulator that can replace humans in implementing these manual operations is of great significance. This manipulator needs to perform three basic functions to complete the procedure: (1) automatically select a part; (2) quickly and accurately place the part in the mouth of the lower die; (3) remove the reshaped part automatically. Note that the vertical space between the upper die and the lower die is relatively small (~70 mm), so neither the SCARA manipulator nor the DELTA manipulator can be applied, and the six-degrees-of-freedom (6-DOF) joint industrial robot does not fully meet the comprehensive application requirements. Powder-metallurgic parts that are ready to be

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Fig. 1. Process of part refining.

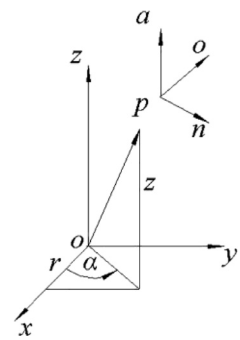

Fig. 2. Cylindrical coordinate system.

refined cannot always be precisely positioned in the picking position; if feeding by vibration set, the state of the parts in the picking position may not be appropriate, having some deviation in the azimuthal or other plane. Therefore, it is essential that some machine-vision is applied. Focusing on the requirements of automatic precision refining of powder-metallurgic parts, correlative theoretical research was conducted using a manipulator to realize the manual operation process, and a prototype mechanical arm was designed and verified.

For the manipulator discussed in this paper, three translational degrees of freedom are required to complete the operation process. If necessary, a pick/place device with a rotational degree of freedom can be installed at the end of the manipulator; this would have a general mechanical interface and an electrical interface with the manipulator. A 3-DOF translation mechanism can choose either a series mechanism or a parallel mechanism. The parallel mechanism has higher positioning precision and lower duplicate localization error [1–3], and the 3-DOF planar parallel mechanism 3-RRR is widely used because of its larger working space [4–7]. Wu [8] analyzed the kinematics of a kind of planar parallel mechanism, and derived a plane displacement equation involving the three driven angles. Bhagat [9] designed a novel flexure-based planar 3-DOF parallel mechanism, which has a compact structure, good rigidity, and capability for fine motion; similar designs have been applied in the field of micro-/nano-scale manipulation and positioning [10–14]. Sellaouti [15] designed and investigated a 3-DOF active mechanism, and analyzed the kinematic characteristics of the mechanism when applied as the joint of a humanoid robot. The parallel mechanism has better adaptability than the series mechanism in the bionic joint [16,17], though the parallel mechanism usually has some singularity [18,19]. Behzadipour [20] designed a 3-DOF cable-based parallel manipulator, proposed a compact structure design method for cable tensioning, and solved the complicated problem of cable tensioning design using a geometric method. Cable-based parallel manipulator platforms have no rigid components, enabling them to achieve high-speed motion [21,22]. This characteristic would be suitable for the automatic work-piece feeding of the manipulator. The planar 3-DOF parallel mechanism can be constructed in a series configuration, parallel configuration, or mixed configuration, each having different kinematic characteristics and bearing capacities [23,24]. The structure design and bearing capacity in different postures and positions of the manipulator must be analyzed in the operation of heavy parts. Mejia [25] analyzed the force characteristics of the 3-RRR planar parallel mechanism and proposed an evaluation method for its bearing capacity. Andrzej [26] designed a 3-DOF tripod-type parallel manipulator and applied it to pick-and-place operations, wherein the movable platform has three degrees of freedom in plane motion; the manipulator uses the 3-UPRR mechanism, originating from the 3-UPU mechanism [27], which can realize planar motion and has direct kinematics solutions [28]. Huang [29] analyzed the kinematic characteristics of the 3-UPU mechanism using helix theory. The practical application of robots proves that motion errors of the end actuator are mainly caused by nominal errors in structural parameters of the mechanism [30], and the application of a calibration method is an effective way of improving the motion precision of the robot [31]. Zhang [32] studied automatic calibration methods for robots based on the binocular vision system, identified the parameters of the mechanism, and investigated to analyze the motion errors. Compared with the parallel mechanism, the 3-DOF series mechanism has a simple kinematic problem, despite suffering a singularity related to the architecture of the mechanism. For example, the 3-RRR series mechanism proposed by Beiner [33] and the SCARA robot [34] mechanism (not including the rotational degrees of freedom of the end member) both suffer from position singularities.

This paper presents a design scheme for a 3-DOF manipulator mechanism based on cylindrical coordinates. This coordinate system not only simplifies the kinematics equations of the mechanism, but also avoids the singularities. In this paper, the principle of mechanism synthesis, inverse kinematics, mechanism dynamics, mechanical structure design method and machine-vision calibration method are studied and analyzed.

2. Mechanism architecture

The cylindrical coordinate system consists of one rotational axis and two translational axes, with three independent dimensional motions. The coordinate system parameters are represented as $\boldsymbol{r}$, α, and z, as shown in Fig. 2. The coordinate system $\boldsymbol{p}$–$\boldsymbol{noa}$ can be obtained by the following sequence of coordinate movements of the basic coordinate system $\boldsymbol{o}$–$\boldsymbol{xyz}$:

(1) Translate the displacement of $\boldsymbol{r}$ along the x axis;
(2) Rotate by an angle of α about the z axis;
(3) Translate the displacement of z along the z axis.

The transformation matrix of the cylindrical coordinates is:

$$\boldsymbol{Cyl}(r, \alpha, z) = \boldsymbol{Trans}(0, 0, z)\boldsymbol{Rot}(z, \alpha)\boldsymbol{Trans}(r, 0, 0) \tag{1}$$

In the manipulator's terminal member, the $\boldsymbol{p}$–$\boldsymbol{noa}$ coordinate system is set, and the coordinate parameters of the origin are represented as any point in the basic $\boldsymbol{o}$–$\boldsymbol{xyz}$ coordinate system; the translational coordinate system is given by multiplying Eq. (1) on the right by a rotational transformation matrix with angle (-α) about the $\boldsymbol{a}$ axis.

The space mechanism based on the cylindrical coordinates has one revolute pair and two prismatic pairs. Using the principle of a link-chain combination, it can be constructed of three series mechanism types, PRP, PPR, and RPP. Each movement of kinematical pairs contains one degree of freedom, so the series mechanism has a total of three degrees of freedom, as shown in Fig. 3(a)–(c).

The three kinds of 3-DOF series mechanisms noted above have different transformation matrix equations, but they have no singular configuration. Series mechanisms (a) and (c) have a larger working space, whereas (b) has higher positional accuracy. From a practical point of view, the mechanism needs a larger working space, and therefore