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Prototype Development of a 5-DOF Series-Parallel Robot Based on 3-PRS Mechanism

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Abstract

Aiming at the problem that the fixed working envelope can not always satisfy the study and experiment requirements, the study has developed a 5-DOF series-parallel robot with an adjustable working envelope based on the 3-PRS mechanism. The robot system is composed of an electric hardware subsystem, a mechanical subsystem and a control system subsystem. The architecture of the robot is introduced firstly. The key components and parts of the electric hardware and mechanical component are presented secondly. The robot system adopts the open architecture mode based on the computer and the motion controller, which provides sufficient convenience for experiments at different levels. Then the control software design method is presented. And many high-level programming languages and Integrated Development Environments can be used separately or together, and even other engineering software packages can be made full use of. Finally, an experiment is presented to verify the developed robot prototype, and that shows its correctness, reliability and convenience.

Keywords*: Series-parallel robot, 3-PRS mechanism, Motion controller, Working envelope*

1. Introduction

Compared with the counterpart, the parallel mechanism, also called parallel robot, has many advantages, such as high stiffness, high accuracy, little cumulate error, large load carrying capacity and compact structure, so it has gained plenty of study and application [1-7]. The parallel mechanism can compensate the disadvantages of the series robot in many peculiar cases. Many parallel robots are always based on the Stewart platform and possess 6 degrees of freedom (DOFs), but the deficient DOF robot has presented prominent performance in some cases. Especially as a typical class, the 3-PRS parallel mechanism possessing 3 DOFs has been widely used because the deficient DOF the structure and control are simpler than the 6 DOFs ones. The 3-PRS parallel mechanism possesses only 3 DOFs and has two parasitic rotational motions and one parasitic translational motion. An X-Y table with two DOFs can be used to compensate the two parasitic rotational motions, so a 5-DOF series-parallel robot can be gotten [3]. There are several key indexes for assessing the performance, such as the volume and the shape of the working envelope, the motion speed, the acceleration, accuracy, and the load carrying capacity. The mechanical structure parameter has heavy influence on the above indexes [8-17]. The robot with the fixed working envelope can not always satisfy the study and experiment requirements. A robot is therefore needed of which the parameter can be adjusted according to the specified requirements. In this paper, a new 5-DOF series-parallel robot with adjustable working envelope based on the 3-PRS mechanism is proposed and the key components and the developing procedure are presented.

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2. Architecture of the 5-DOF Series-Parallel Robot

The 5-DOF series-parallel robot is mainly composed of a 3-PRS parallel mechanism and a 2-DOF X-Y table as shown in Figure 1 [1, 3-5, 7, 21]. The key component is a 3-PRS parallel mechanism. This mechanism is composed of a moving platform, three limbs, three vertical rails and a fixed platform (base). Three vertical rails vertically link to the fixed platform (base) B_1 B_2 B_3. Moreover, B_1 B_2 and B_3 form an equilateral triangle that lies on a circle with the radius R. The axis of each revolute pair c_i for $i=1,2$ and 3 is perpendicular to the corresponding prismatic pair. Each limb L_i for $i=1,2$ and 3 with the length of l_i connects the corresponding rail by a prismatic pair C_i. The moving platform and three limbs are connected by three spherical pairs P_1, P_2 and P_3.

Three spherical pairs form an equilateral triangle that lies on a circle with the radius r. The cutter with the length of h is placed at the center of the moving platform. The feeds of the three prismatic pairs are given as H_i for $i=1,2$ and 3. The angle θ_i for $i=1,2$ and 3 is defined from the vertical rail to its corresponding limb L_i. As shown in Figure 1, a fixed Cartesian reference coordinate system OXYZ is located at the center point O of B_2 B_3. The X-axis and the Y-axis are in the base plane B_1 B_2 B_3, the X-axis points in the direction of O B_1, and the Z-axis is normal to the base plane and points upward. A moving coordinate system o_T xyz is located on the moving platform. The position and orientation of the cutter can be described using the coordinates $(x_{Tool}, y_{Tool}, z_{Tool})$ of the cutter point P and Euler angles α, β and γ rotating about the Z, Y and X axes of the fixed system, respectively. The 3-PRS parallel mechanism possesses 3 DOFs that are a rotational motion α about the the Z-axis, a rotational motion β about the Y-axis, and a translational motion z_T along the Z-axis. Three parasitic motions are one rotational motion γ, one translational motion x_{PT} about the X-axis and one translational motion y_{PT} about the Y-axis. The three parasitic motions γ, x_{PT} and y_{PT} can be expressed using the three independent motions α, β and z_T.

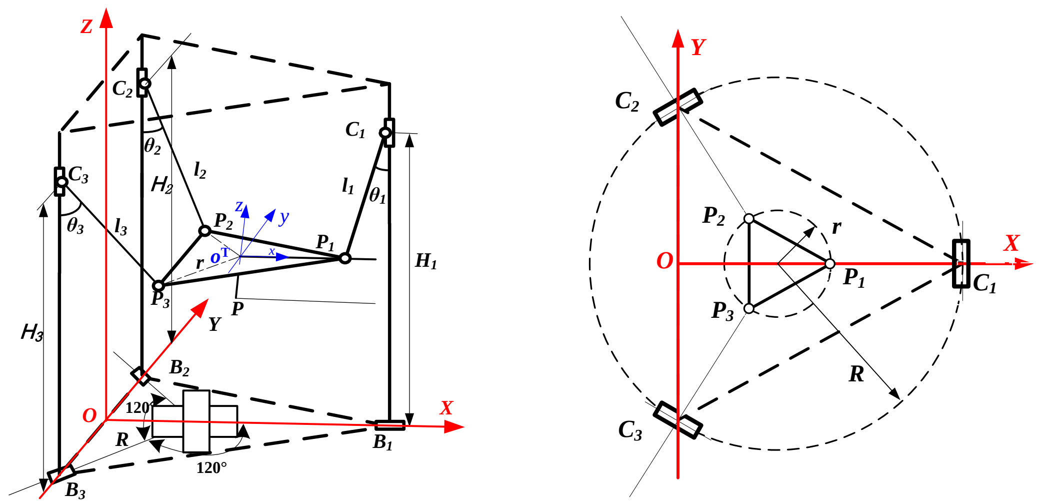

Figure 1. The Schematic Diagram of the 5-DOF Series-Parallel Robot

Restricted by the three revolute pairs and three spherical pairs, the limbs L_1, L_2 and L_3, and three spherical pairs P_1, P_2 and P_3 can only move in the three planes $\Omega_1, \Omega_2, \Omega_3$, respectively, shown in Figure 2.

$$\begin{cases} \Omega_1\text{:}\ \ Y = 0; \\ \Omega_2\text{:}\ \ Y = -\sqrt{3}\left(X - R/2\right) \\ \Omega_3\text{:}\ \ Y = \sqrt{3}\left(X - R/2\right) \end{cases} \tag{1}$$

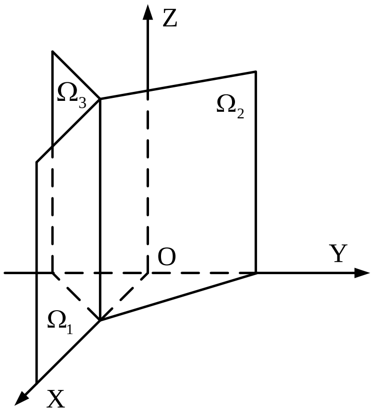

Figure 2. The Movement Planes of the Three Limbs

An X-Y table possesses two DOFs. Along with the 3 DOFs of the 3-PRS mechanism, the series-parallel robot shown in Figure 1 possesses 5 DOFs that are

(1) the rotational motion α about the Z-axis
(2) the rotational motion β about the Y-axis
(3) the translational motion x_{T} along the X-axis
(4) the translational motion y_{T} along the Y-axis
(5) the translational motion z_{T} along the Z-axis.

The parasitic rotational motion, Euler angle, γ that can be expressed by the other two angles α and β using Equation (2).

$$\gamma = -\arctan\frac{\sin\alpha \cdot \sin\beta}{\cos\alpha + \cos\beta} \tag{2}$$

The parasitic translational motions x_{PT} and y_{PT} that can be computed using Equation (3).

$$\begin{cases} x_{\mathrm{PT}} = \dfrac{r}{2}\left(\cos\beta\cos\gamma + \sin\alpha\sin\beta\sin\gamma - \cos\alpha\cos\gamma\right) - h\sin\beta + \dfrac{R}{2} \\ y_{\mathrm{PT}} = h\sin\alpha\cos\beta - r\sin\alpha\sin\beta\cos\gamma - r\cos\alpha\sin\gamma \end{cases} \tag{3}$$

The 2-DOF X-Y table is utilized to compensate the parasitic motions x_{PT} and y_{PT}, to get the expected coordinates along the X-axis and the Y-axis. And this provides the translational motions x_{T} and y_{T}.

3. Electric Hardware and Mechanical Component Design

The open structure is adopted to develop the 5-DOF series-parallel robot and the structure is based on the mode of the computer and the motion controller/control card as shown in Figure 3. This structure provides much convenience to control the robot motion using many high level programming languages and control the motion laws of the motor directly through several methods. Six motors are used in the robot. Three permanent magnet synchronous motors (PMSM) are used as the actuating motors to drive the three vertical rails based on ball screw units. Two motors for the 2-DOF X-Y table are stepper ones. And the spindle motor is a brushless direct current motor (BLDCM). Each motor is controlled and driven by a driver and controller. An 8-axis motion control card/controller GT 800-PV made by Googol Technology Limited is used to control the 6 motors. The IPC (Industrial Personal Computer) sends control signals to the driver and controller through the motion control card. The three PMSMs can be controlled though three modes: speed, position and torque. Three grating rulers are used to measure the motion position of the three vertical rails.

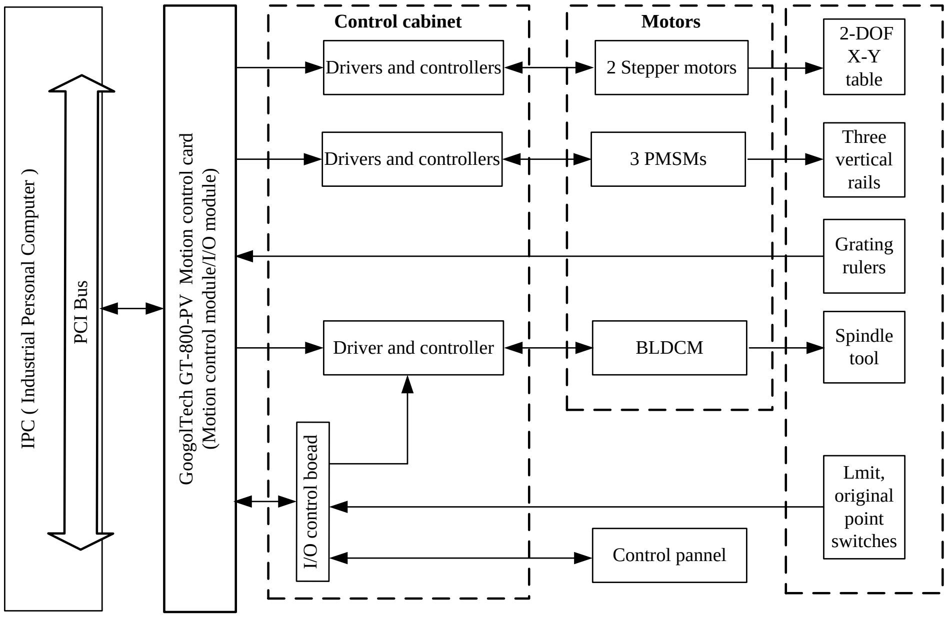

Figure 3. The Whole Configuration of the Robot

The mechanical part of the 5-DOF series-parallel robot is designed and its workspace is adjustable instead of the traditional fixed one. The adjustment is realized through changing the radius R of the 3-PRS parallel mechanism as shown in Figure 4, and the fixed platform (base) and its affiliated parts are shown in Figure 5. The adjustable robot has the following advanced features.

(1)The adjustable 3-PRS mechanism is also composed of three branches. Each vertical trail is connected to the fixed base through a prismatic pair. And the adjustable range is

$$300\text{mm} \le R \le 600\text{mm} \tag{4}$$

(2)Each adjustable prismatic pair is composed of a trapezoid slider and a trapezoid sliding block. The vertical trail is fixed on the sliding block vertically. The sliding block slides along the corresponding slider to adjust the radius R .

(3) The assembly of the sliding block and the slider is positioned using the upper plane surfaces and one-lateral plane surfaces. And the sliding block is clamped to the slider through a panel and screws along the other lateral plane surfaces after adjustment.

(4)Three keys are set to guarantee the angle between the central axes of the three adjustable prismatic pairs. And the theoretical angle is 120° .

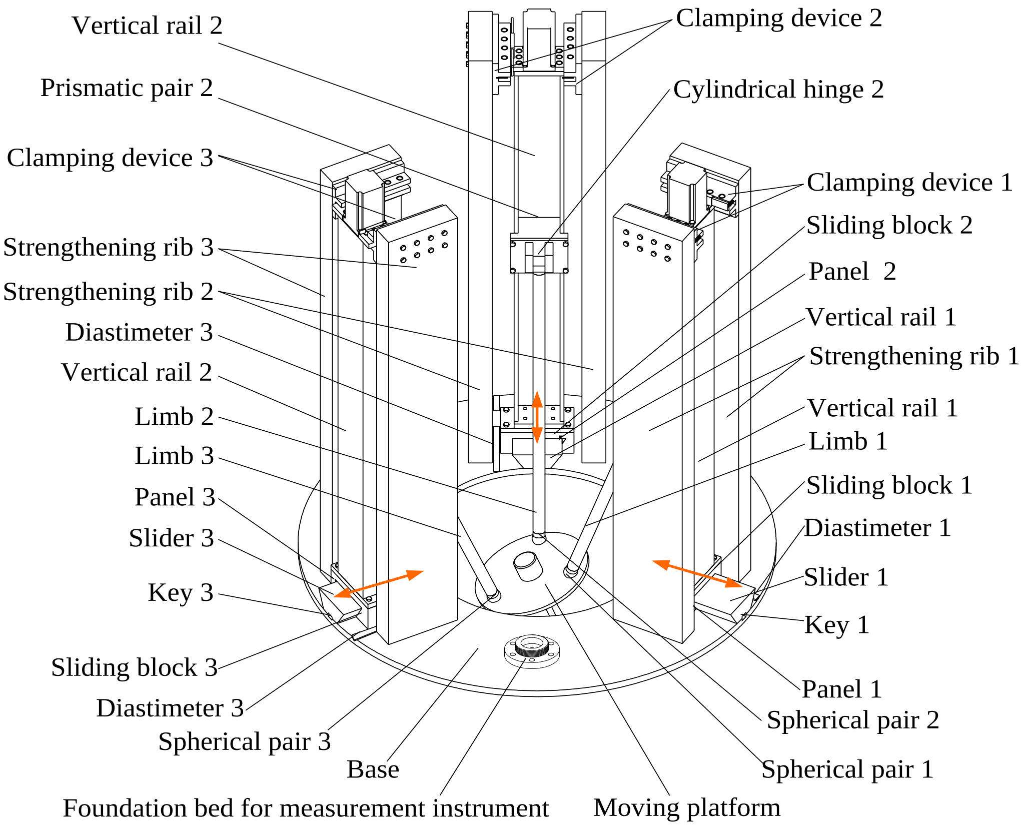

Figure 4. Three-Dimensional Model of the Adjustable 3-PRS Parallel Mechanism

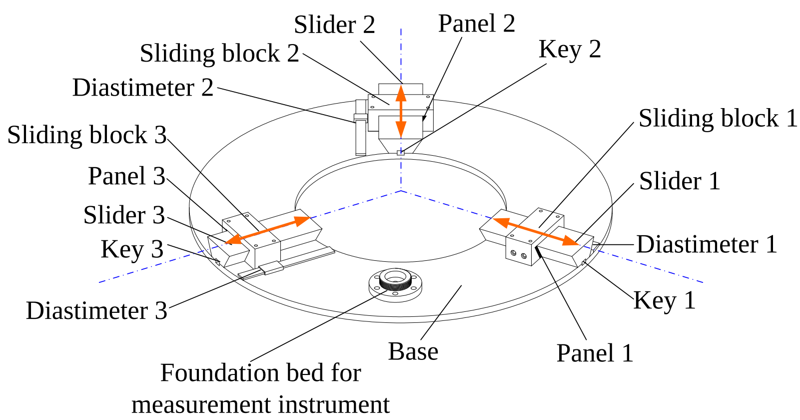

Figure 5. The Schematic Diagram of the Fixed Platform (Base) and Its Affiliated Parts

(5)The diastimeter is mounted beside the trapezoid slider to measure and display the adjusting distance, which provides convenient and visual help to the user.

(6)The two strengthening ribs are set on the both sides of each vertical trail. And this structure can also be substituted by a triangular frame fixed on the top of the three vertical trails. Those structures can reduce the deformation of the vertical trails efficiently.

Two bearings are used, and the cylindrical hinge is shown in Figure 6. The connection method of the cylindrical hinge and the spherical pair is shown in Figure 7. The moving platform and three limbs are connected by three spherical pairs as shown in Figure 7. The angle δ is a key parameter of the spherical pair, and is vital to the strength itself and the working envelope of the robot. After repeating simulation and analysis, the angle δ is set as 90° here. The machining and assembly accuracy of the spherical pairs has significant influence on the accuracy of the position and attitude of the robot. In order to reduce the assembly error, the three ball sockets and the moving platform are machined as a whole part, as shown in Figure 8. The whole part is machined using the CNC (Computer Numerical Control) milling machine.

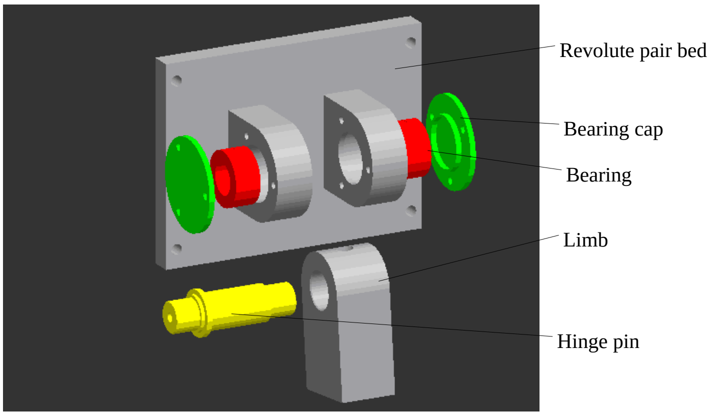

Figure 6. The 3D Assembly Model of the Cylindrical Hinge

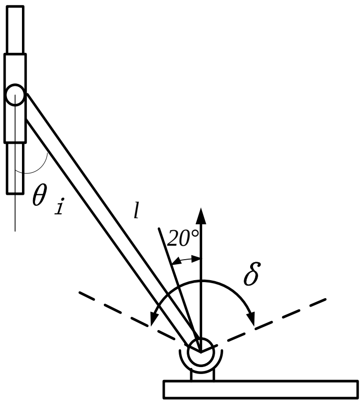

Figure 7. The Revolute Pair and The Spherical Pair

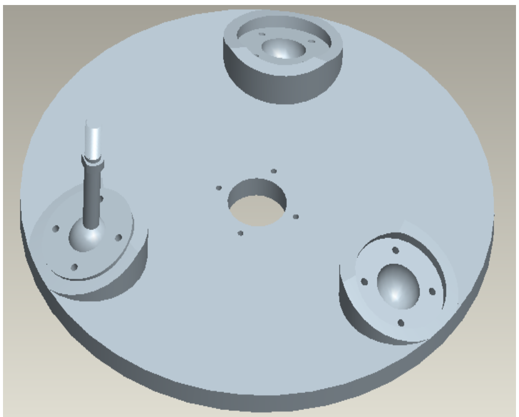

Figure 8. The 3D Assembly Model of the Moving Platform

The main geometric parameters of the robot are shown in Table 1.

Table 1. The Main Geometric Parameters of the Robot

Maximum R	Slider distance	r	Limb length l	δ
600mm	150mm	150mm	820mm	90°

4. Control Software Design

The control software architecture is shown in Figure 9. The key is to control the motion laws of the driving motors through the motion control card. The Dynamic Link Library (DLL) gts.dll and IExtMdl.dll are provided to control the motion module and I/O module. Various functions in the DLLs can be called to control the position and attitude of the robot, measure the state and feed the fault through the high-level programming language and Integrated Development Environments (IDEs), such as Visual Basic, Visual C++ and C++ Builder. Even the engineering software can be integrated together. Sometimes this is necessary because the direct and inverse kinematics is always very complicated and more difficult to compute in many high level languages [18-21]. For example, MATLAB can be used for numerical computation and visualization that are complicated in many other development environments.

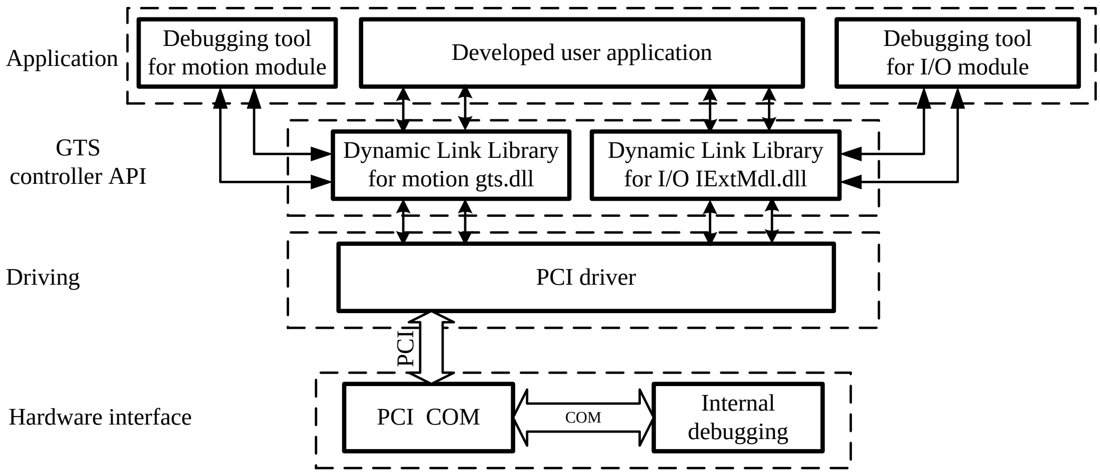

Figure 9. The Control Software Architecture

5. The Developed Prototype and Experiment

The developed 5-DOF series-parallel robot prototype is shown in Figure 10 to Figure 12. In order to verify the developed robot, an experiment is done. The trajectory of the cutter point is a circle with the diameter of 10cm. And the intersection angle between the cutter and the Z-axis is 20° shown in Figure 13. If a time variable is introduced, the three Euler angles can be computed. Based on the inverse kinematics and Equation (3) the cutter, the X-Y table and the synthetic trajectories has been gotten as shown in Figure 14. The feeds of the three pairs have been computed using MATLAB in advance and imported to the control application. In the experiment, the position time (PT) motion mode has been adopted. In this mode, the feed and the time should be discretized and stored in the array, and the position is reflected as pulses. The prospective pre-processing function of the controller is used to improve the motion performance of the robot. The running results are shown in Figure 15.

Figure 10. The Moving Platform

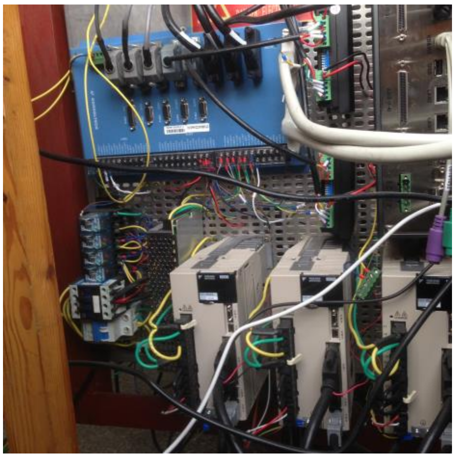

Figure 11. The Controllers and Motor Drivers

Figure 12. Pictures of the 5-DOF Series-Parallel Robot

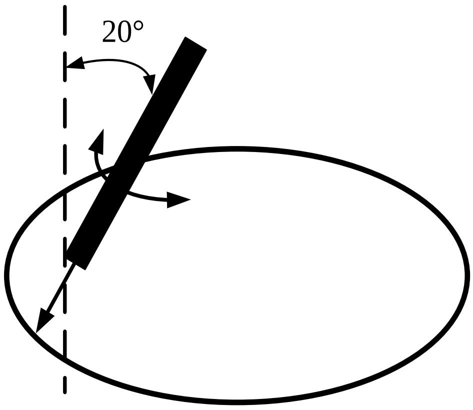

Figure 13 The Attitude, Position and Trajectory of the Cutter

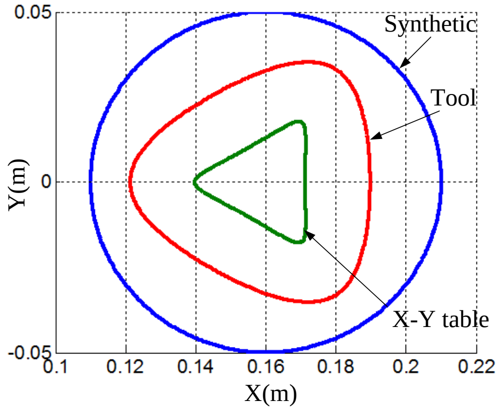

Figure 14 The Cutter, the X-Y Table and the Synthetic Trajectories

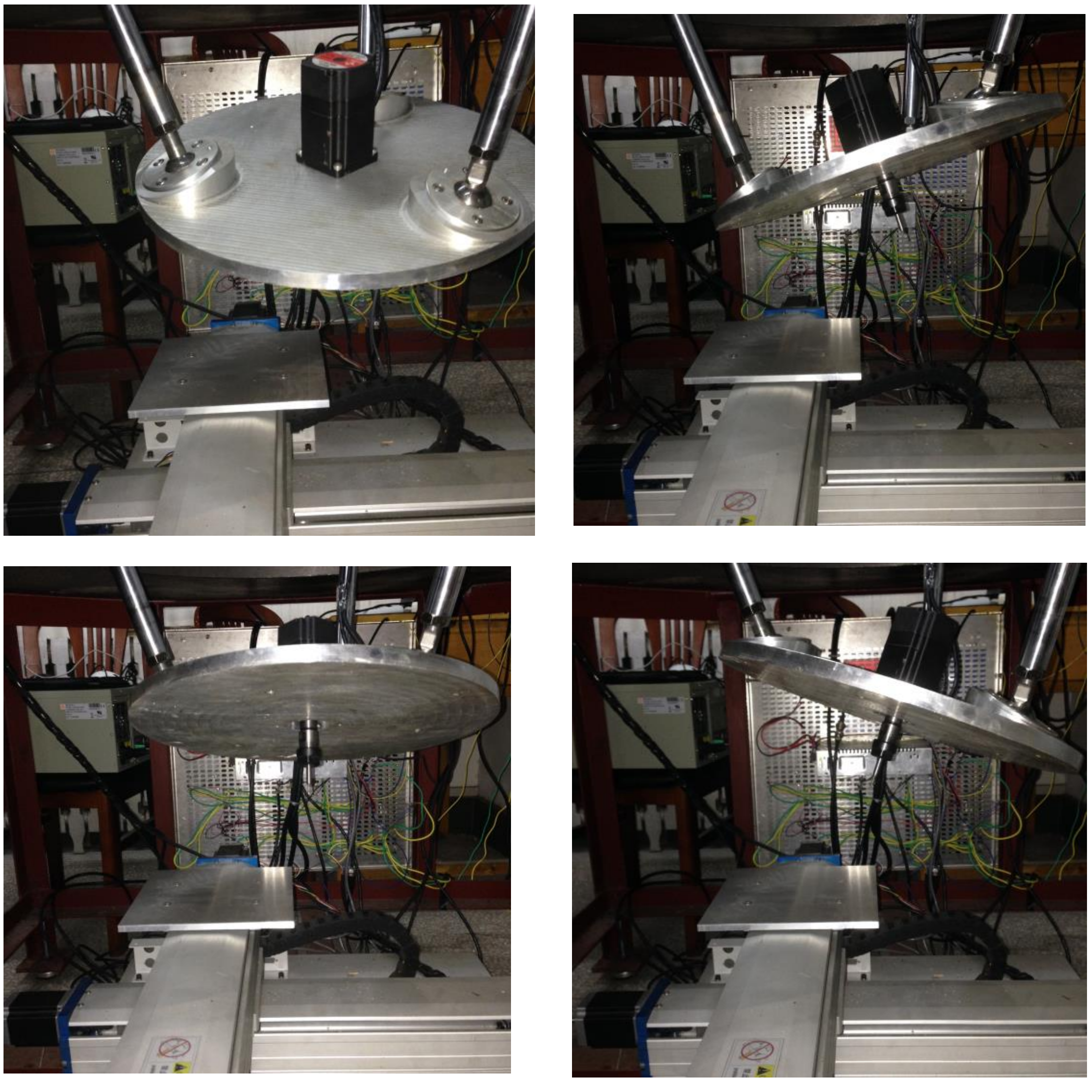

Figure 15. The Running Results

6. Conclusions

A 5-DOF series-parallel robot with an adjustable working envelope based on 3-PRS mechanism has been developed and the key components are given. The developed robot system has several features and advantages. Firstly, the robot system adopts the open architecture mode based on the computer and the motion controller, which provides sufficient convenience for experiments at different levels. In addition, this robot uses 6 motors including 3 PMSMs, 2 stepper motors and one BLDCM, which facilitate the verification of the control method and performance of different motors in the robot system. Thirdly, the adopted motion controller provides DLLs that are composed of many functions and make it easy to control and measure the state of the robot efficiently. And many high-level programming language and IDEs can be used separately or together, and even other engineering software can be made full use of. Finally, the mechanical component has been designed as adjustable one, so the working envelope can be adjusted to satisfy the specified research objective. However, it should be noticed that the 3-PRS mechanism can be classified into seven kinds according to limb arrangements as discussed in [21]. The mechanical component proposed in the paper can be modified for other kinds. In addition, the precision and its measurement are very important tasks in the series-parallel robot study, so the robot should be studied in depth in these aspects. This will be our future work.

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