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Design of a novel 5-DOF parallel kinematic machine tool based on workspace

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SUMMARY

In this paper an inverse concept idea is presented to determine the main configuration dimensional parameters of a novel 5-DOF parallel kinematic machine tool. By the new described orientation workspace, the motion of the passive joints on the moving platform can be expressed in the fixed coordinate analytically. Some relationships between the reachable workspace and the dimensional parameters of the parallel machine tool have been obtained with graphical representation.

KEYWORDS: Parallel tool; Inverse energy; Reachable workspace; Dimensional parameter.

1. INTRODUCTION

Parallel manipulators have been studied by many researchers for half a century. Now parallel manipulators have been applied to many fields, for examples, flight simulators, machine tools, force/torque sensors, micromanipulators and so on. Each of these applications has quite different requirements of performance. Merlet[1] presented the lemma that a mechanical architecture, which may seem to be more appropriate for a given task and whose dimensions have been chosen arbitrarily will perform more poorly than another mechanical architecture whose dimensions have been carefully selected. Therefore, it is a very important problem to design the dimensions of parallel manipulators in accordance with their requirements.

For a dimensional design of parallel kinematic machine tools one has to decide the configuration parameters with the aim of realizing the required performance. Pittens[2] obtained a local optimum dexterity configuration in a special constraint by a numerical method. Zanganeh[3] obtained the same result as Pittens by taking isotropy as the evaluating criterion. Gosselin and Angeles[4] studied the configuration parameters design method considering the workspace and controlled dexterity simultaneously by global dexterity. Gao[5] proposed a method for the type design of 2-, 3-, 4-, 5- and 6-DOF parallel manipulators.

In this paper we focus on the main configuration parameter design of a novel 5-DOF parallel machine tool while considering the reachable workspace.

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2. DESCRIPTION OF THE PARALLEL MACHINE TOOL

The structure of the parallel kinematic machine tool proposed by us[5] is shown in Fig. 1. Five limbs connect the moving platform to the fixed platform. The four limbs consist of an actuated linear slide, a passive spatial joint, a fixed-length strut and a passive universal joint, respectively. The 5th limb consists of an actuated linear slide, a special mechanical architecture noted U^* (Fig. 2) and a passive universal joint. Thus the 5-DOF parallel mechanism can be named $4-PSU$ & $1-PU^*U$.

The five degrees of the freedom parallel kinematic machine tool are represented schematically in Fig. 3.

For the purpose of kinematics analysis, a fixed coordinate frame $o - xyz$ noted R_B is attached to the fixed platform, and a moving frame $o' - x'y'z'$ noted R_A is attached to the moving platform (Fig. 3). The position of point $A_i (i = 1 \sim 4)$—the ith $(i = 1 \sim 4)$ passive universal joint connected to the moving platform—is therefore constant when expressed in the frame R_A. Similarly, the position of point $B_i (i = 1 \sim 4)$—the ith $(i = 1 \sim 4)$ passive spatial joint connected to the fixed platform—is therefore constant when expressed in the frame R_B. The components of the position of point $A_i (i = 1 \sim 4)$ in the frame R_A will be denoted by x_{ai}, y_{ai} and z_{ai} and the components of the position of point $B_i (i = 1 \sim 4)$ in the frame R_B will be denoted by x_{bi}, y_{bi} and z_{bi}. The Cartesian coordinates of the parallel kinematic machine tool are defined as the position of point o' with respect to the point o and denoted by (x,y,z). Moreover, the actuated joint coordinates are given by the position of the linear slides along the y-axis in the frame R_B.

Let(θ, ϕ) denote the rotation angles defined by rotating the moving platform first about the z-axis by a θ degree, then about x-axis by a ϕ degree, as shown in Fig. 4. The physical dimensions of the moving platform are shown in Fig. 5.

3. DIMENSIONAL DESIGN METHOD

The configuration dimensions of the parallel kinematic machine tool affect its performance. In general, it is very difficult to satisfy all performance criteria for a given set of dimensions. So, it is necessary to focus on the main performance requirements when designing a parallel manipulator. In this paper we focus on the reachable workspace requirement of the 5-DOF parallel kinematic machine tool and study the relationship between the reachable workspace and the main dimensions of the parallel kinematic machine tool.

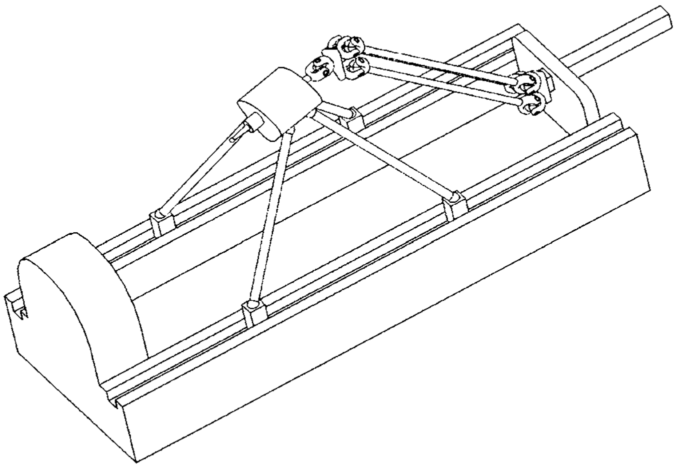

Fig. 1. 5-DOF parallel kinematic machine tool.

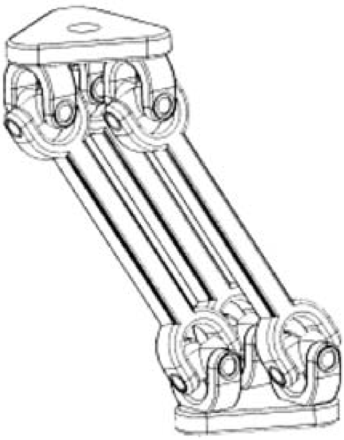

Fig. 2. The special mechanical architecture U^*.

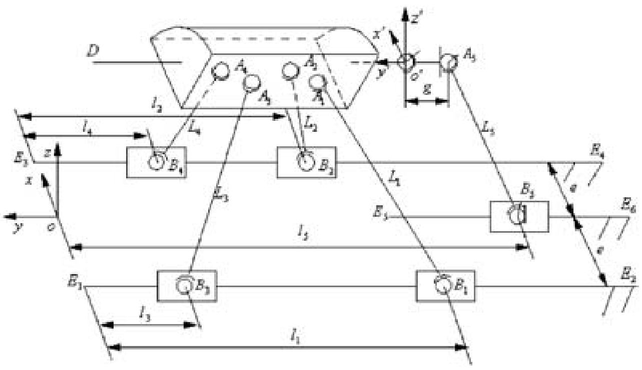

Fig. 3. The schematic architecture of the machine tool.

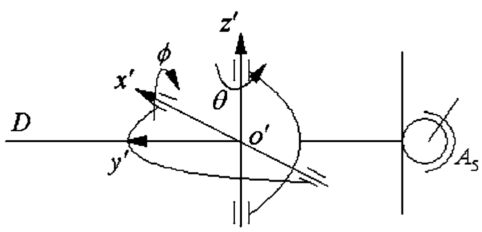

Fig. 4. Rotation angles defining approach vector for the moving frame.

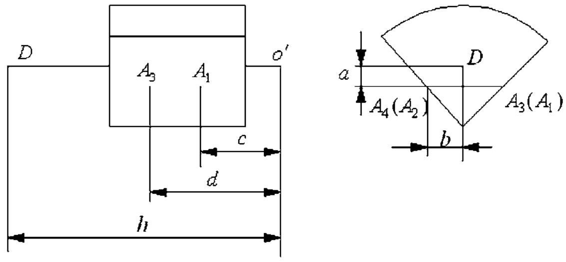

Fig. 5. Physical dimensions of the moving platform.

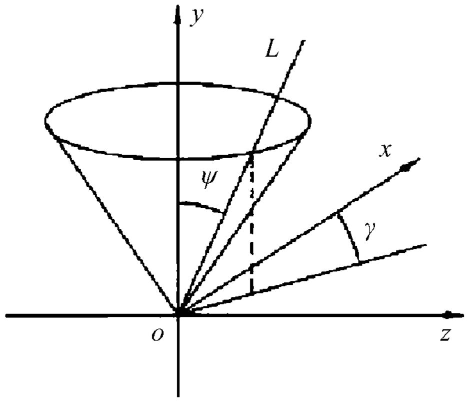

Fig. 6. The azimuth of the spindle.

The reachable workspace can be determined if we knew the configuration dimensions of the parallel kinematic machine tool. The motion of the passive joints on the moving platform can be obtained by the coordinate transform. The maximum distance between the passive joints on the moving platform and the ones on the actuated linear slides can be obtained. The maximum distance is just the minimum value of the strut parameter. Thus the relationship between the reachable workspace and the configuration dimensions can be obtained by the analytical method. It is the inverse thinking concept that is used to determine the main configuration of the novel 5-DOF parallel kinematic machine tool.

4. APPLICATION

In practice, we must consider the position of the point and the direction of the spindle. For the purpose of analysis, we describe the azimuth of the spindle by two angles of sector (Fig. 6). The angle γ is defined as the direction angle, and the angle ψ is defined as the angle of inclination.

In the cutting process it is required that the spindle would incline in any direction. So, the range of the angle γ is $[0, 2\pi]$. The angle ψ describes the oblique capability of the spindle. The relationship between the angles (θ, ϕ) and the angles (ψ, γ) can be easily obtained:

$$\begin{cases} \cos\phi = \sqrt{1-\sin^2\psi\sin^2\gamma} \\ \sin\phi = -\sin\psi\sin\gamma \\ \cos\theta = \dfrac{\cos\psi}{\sqrt{1-\sin^2\psi\sin^2\gamma}} \\ \sin\theta = \dfrac{\sin\psi\cos\psi}{\sqrt{1-\sin^2\psi\sin^2\gamma}} \end{cases} \tag{1}$$

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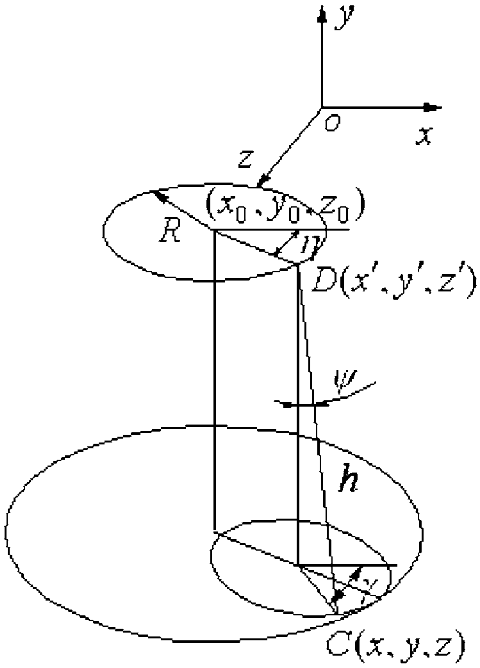

Fig. 7. The relationship between the reachable workspace on a given plane and the pose of the moving platform.

Actually, we do not need all the reachable workspace of the parallel machine tool, but a subset with a very regular shape. In general, a columned reachable workspace is required for a parallel kinematic machine tool for its special configuration arrangement. What's more, we can draw the conclusion that the 5-DOF parallel mechanism has two characteristics: identical performance and symmetrical performance. The identical performance is that the moving platform can be moved entirely when all the actuated linear slides have the same velocity. Thus we can only consider a sectional plane of the reachable workspace. Fig. 7 shows the relationship between the reachable workspace on a given plane and the pose of the moving platform. In Fig. 7 point $D(x', y', z')$ is the end point of the cutter, point $C(x, y, z)$ is the origin of the moving coordinate frame, R denotes the maximum radius of the inscribed circle of the reachable workspace on a given plane, point (x_0, y_0, z_0) is the center of the machining, and h is the distance between the point C and the point D.

From the Fig. 7, one can obtain:

$$\begin{cases} x = x_0 + R\cos\eta + h\sin\psi\cos\gamma \\ y = y_0 - h\cos\psi \\ z = z_0 + R\sin\eta + h\sin\psi\sin\gamma \end{cases} \quad \begin{pmatrix} 0 \le \eta \le 2\pi \\ 0 \le \gamma \le 2\pi \end{pmatrix} \tag{2}$$

Thus the position of the passive joint A_5 in the fixed coordinate frame can be written as $(x, y - g, z)$. The minimum distance between the passive joints A_5 and B_5 can be expressed as

$$\begin{aligned} L_5^2 &= (x_0 + R\cos\eta + h\sin\psi\cos\gamma)^2 \\ &\quad + (z_0 + R\sin\eta + h\sin\psi\sin\gamma)^2 \\ &\quad (0 \le \eta \le 2\pi, 0 \le \gamma \le 2\pi) \end{aligned} \tag{3}$$

By the symmetrical performance, the value of x_0 can be equal to zero. The value of L_5^2 will reach the maximum when $\eta = \gamma = \frac{\pi}{2}$.

$$L_{5\,\max}^2 = (z_0 + R + h\sin\psi)^2 \tag{4}$$

The fixed length strut parameter L_5 can be easily determined if the required reachable workspace is given.

For the same reason, the minimum distance between the other passive joints can be obtained.

$$\begin{aligned} L_1^2 = &\left(R\cos\eta + h\sin\psi\cos\gamma - b\frac{\cos\psi}{\sqrt{1-\sin^2\psi\sin^2\gamma}}\right. \\ &\left. - c\sin\psi\cos\gamma + a\frac{\sin^2\psi\sin\gamma\cos\gamma}{\sqrt{1-\sin^2\psi\sin^2\gamma}} + e\right)^2 \\ &+ (z_0 + R\sin\eta + h\sin\psi\sin\gamma - c\sin\psi\sin\gamma \\ &- a\sqrt{1-\sin^2\psi\sin^2\gamma})^2 \\ &(0 \le \eta \le 2\pi, 0 \le \gamma \le 2\pi) \end{aligned} \tag{5}$$

$$\begin{aligned} L_2^2 = &\left(R\cos\eta + h\sin\psi\cos\gamma + b\frac{\cos\psi}{\sqrt{1-\sin^2\psi\sin^2\gamma}}\right. \\ &\left. - c\sin\psi\cos\gamma + a\frac{\sin^2\psi\sin\gamma\cos\gamma}{\sqrt{1-\sin^2\psi\sin^2\gamma}} - e\right)^2 \\ &+ (z_0 + R\sin\eta + h\sin\psi\sin\gamma - c\sin\psi\sin\gamma \\ &- a\sqrt{1-\sin^2\psi\sin^2\gamma})^2 \\ &(0 \le \eta \le 2\pi, 0 \le \gamma \le 2\pi) \end{aligned} \tag{6}$$

$$\begin{aligned} L_3^2 = &\left(R\cos\eta + h\sin\psi\cos\gamma - b\frac{\cos\psi}{\sqrt{1-\sin^2\psi\sin^2\gamma}}\right. \\ &\left. - d\sin\psi\cos\gamma + a\frac{\sin^2\psi\sin\gamma\cos\gamma}{\sqrt{1-\sin^2\psi\sin^2\gamma}} + e\right)^2 \\ &+ (z_0 + R\sin\eta + h\sin\psi\sin\gamma - d\sin\psi\sin\gamma \\ &- a\sqrt{1-\sin^2\psi\sin^2\gamma})^2 \\ &(0 \le \eta \le 2\pi, 0 \le \gamma \le 2\pi) \end{aligned} \tag{7}$$

$$\begin{aligned} L_4^2 = &\left(R\cos\eta + h\sin\psi\cos\gamma + b\frac{\cos\psi}{\sqrt{1-\sin^2\psi\sin^2\gamma}}\right. \\ &\left. - d\sin\psi\cos\gamma + a\frac{\sin^2\psi\sin\gamma\cos\gamma}{\sqrt{1-\sin^2\psi\sin^2\gamma}} - e\right)^2 \\ &+ \big(z_0 + R\sin\eta + h\sin\psi\sin\gamma - d\sin\psi\sin\gamma \\ &- a\sqrt{1-\sin^2\psi\sin^2\gamma}\big)^2 \\ &(0 \le \eta \le 2\pi, 0 \le \gamma \le 2\pi) \end{aligned} \tag{8}$$

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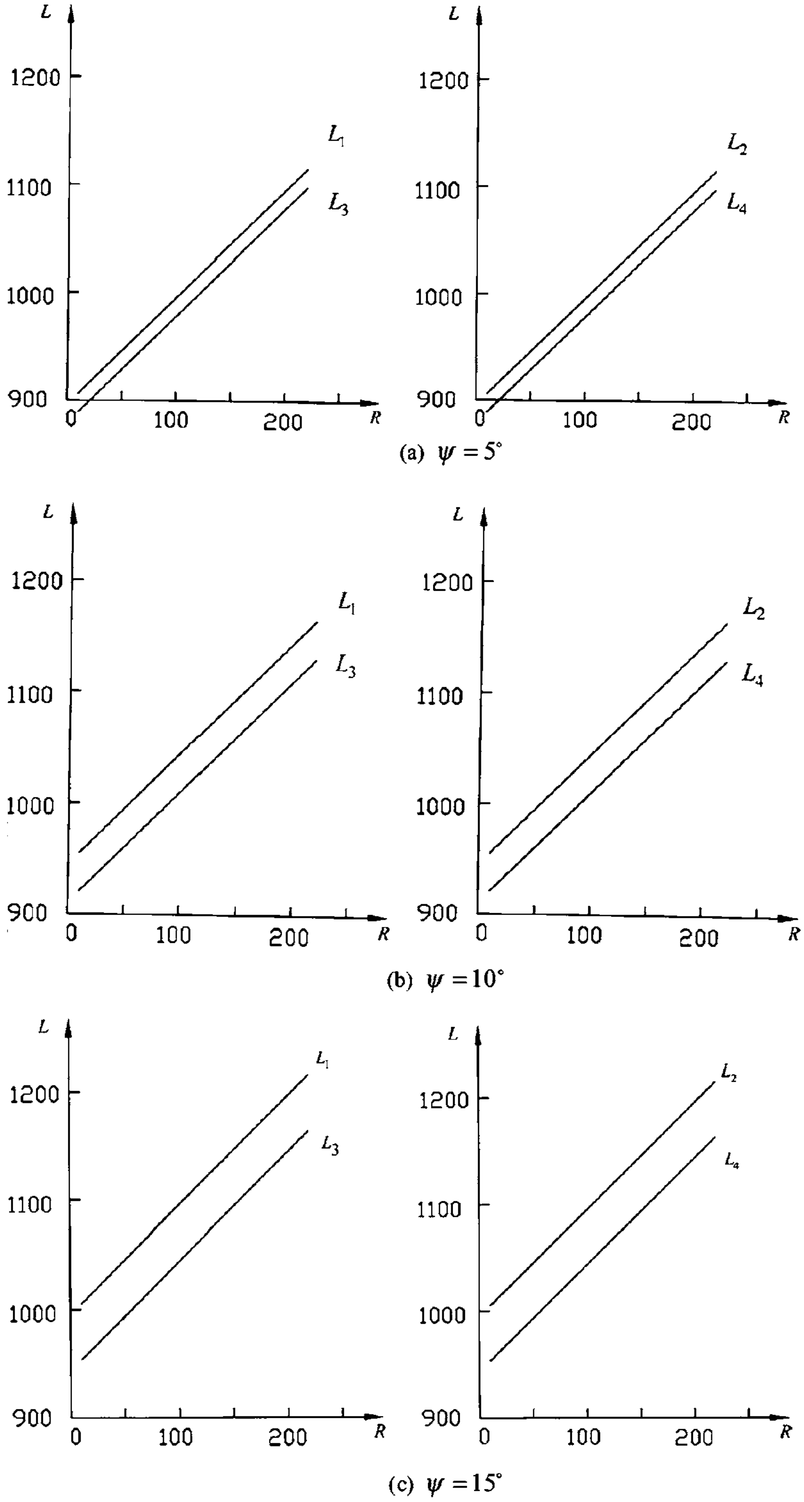

Fig.8. For caption see facing page.

Fig. 8 shows the relationship between the radius of the maximum inscribed circle and the minimum length of the struts with different angles of inclination.

From the Fig. 8, the following conclusions can be obtained:

- The change of the length curves of the struts L_1 and L_2 or L_3 and L_4 is consistent. It can be explained for the symmetrical performance of the parallel machine tool.
- The required minimum length of the struts is increased with the larger radius of the maximum inscribed circle or the larger angles of inclination.
- The dispersion of the required minimum lengths of the struts L_1 and L_3 or L_2 and L_4 is larger with the larger angles of inclination.

During the design one can easily meet the requirement of the length of the struts if the design dimensions are larger

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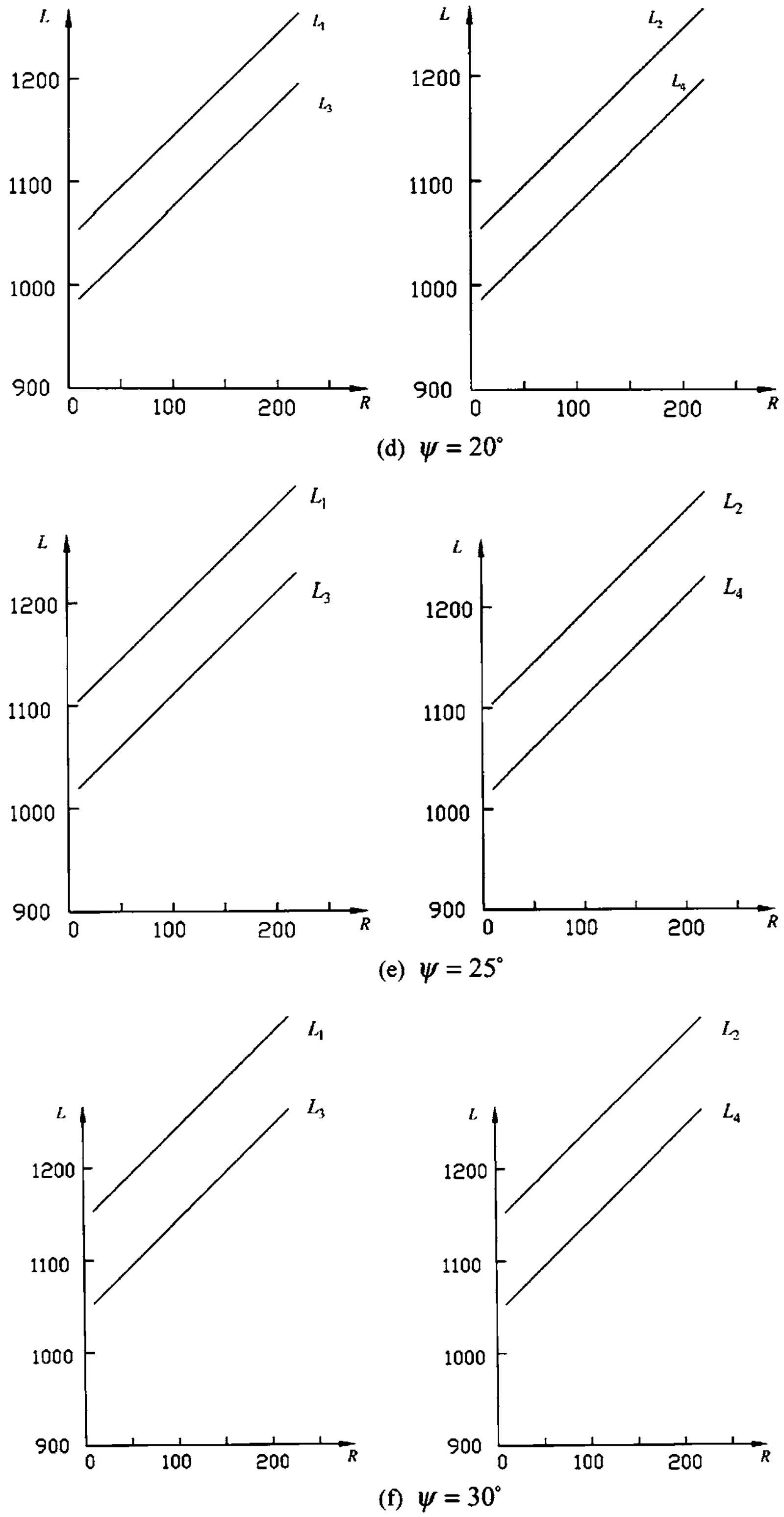

Fig. 8. The relationship between the radius of the maximum inscribed circle and the minimum length of the struts with different angles of inclination.

than the maximum value of the expression of the minimum length of the struts. Now we show how to determine the range of the motion of the five actuated linear slides. For the same reason presented above, the inverse kinematics of the parallel machine tool and the range of the motion of the linear slides can be determined. Fig. 9 shows the relationship between the radius of the maximum inscribed circle of the reachable workspace on a given plane and the range of the motion of the linear slides.

The range can only satisfy the motion of the end-effector in a given plane. By the identical performance the end-effector can be moved in a columned reachable workspace if the range of the motion of the linear slides augments the same length along the same direction.

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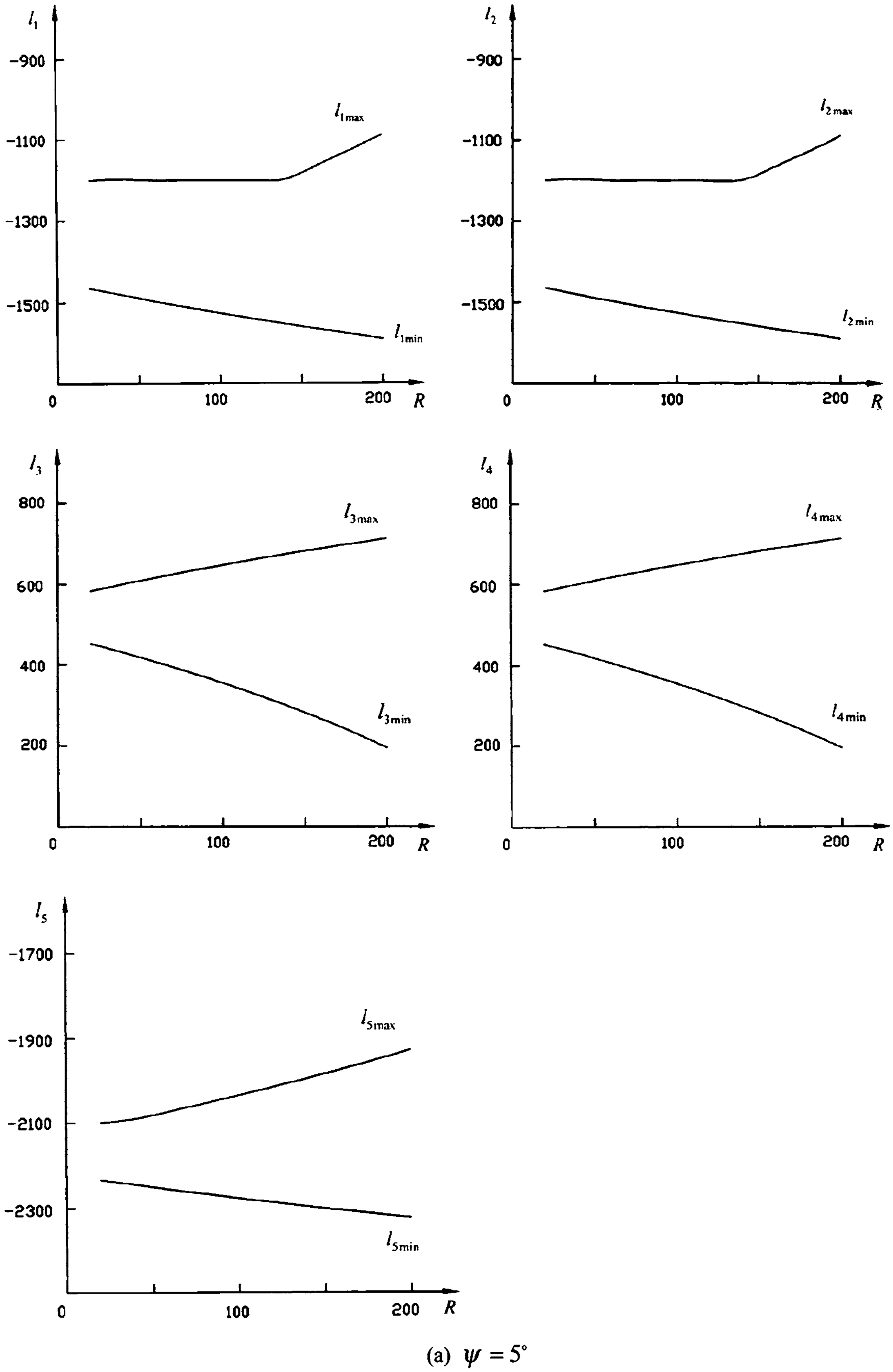

Fig. 9. For caption see page no. 8.

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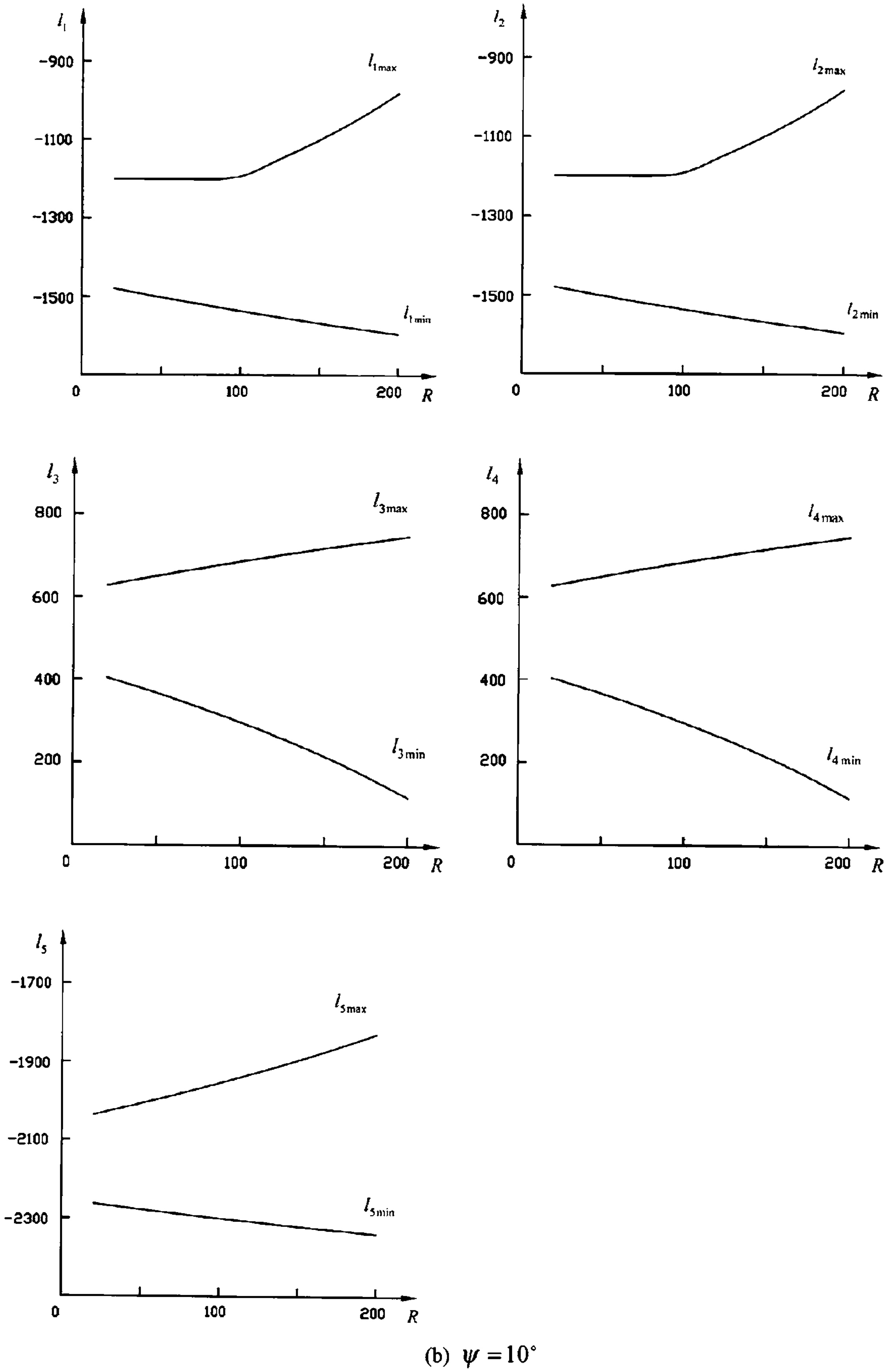

(b) $\psi = 10°$

Fig. 9. For caption see page. no. 8.

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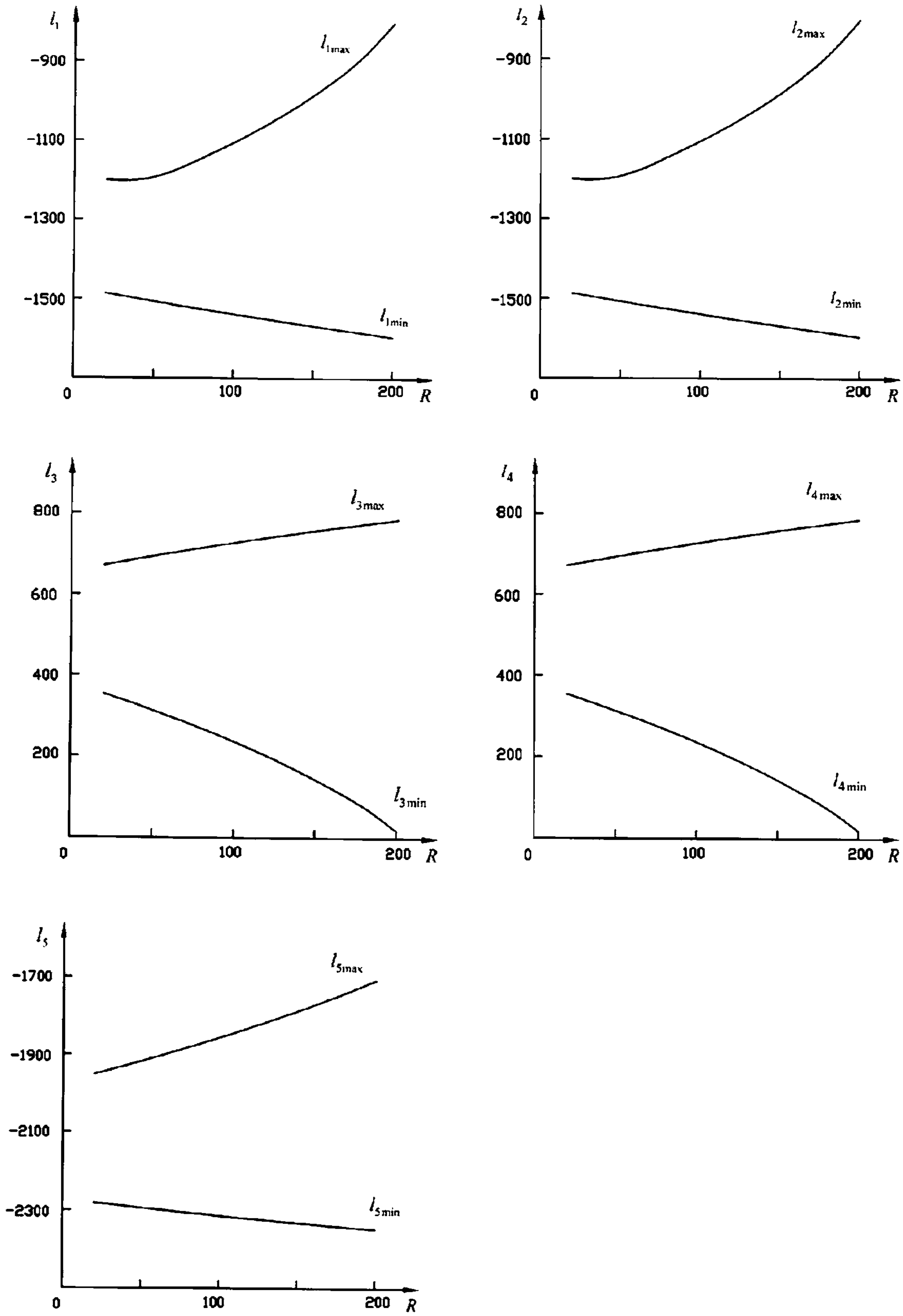

(c) $\psi = 15°$

Fig. 9. Relationship between the radius of the maximum inscribed circle and the range of the motion of the linear slides.

Fig.10. The prototype of the 5-DOF parallel kinematic machine tool.

Table I. The architecture parameters of the parallel kinematic machine tool (mm).

a	106.066
b	162.635
c	260.000
d	460.000
e	650.000
g	220.000
L_i $(i = 1 \sim 4)$	1215.000
L_5	1400.000

A parallel kinematic machine tool based on the above design has been built at the Hebei University of Technology, in China. The prototype is shown in Fig. 10, which has a columned workspace (ϕ 400 × 400) with a certain angle of inclination ($\psi = 15°$). The value of the design parameters arrived by it are given in the table I.

5. CONCLUSIONS

Considering a reachable workspace, this paper presents a new method to determine the configuration architecture parameters of a new novel 5-DOF parallel kinematic machine tool. The method makes it possible for us to describe the relationship between the reachable workspace and the configuration dimensional parameters of the parallel machine tool in analytical expressions. Some graphical representation has been obtained to illustrate the relationship.

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