Kinematics Analysis of the Parallel Mechanism with Vertically Fixed Linear Actuators*

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A 6 degrees of freedom parallel mechanism actuated by vertically fixed linear actuators was developed for heavy material handling and machining. The mechanism allows easy trajectory generation, since the vertical arrangement of the linear actuators simplifies the calculation of its inverse kinematics. This paper presents inverse kinematics and Jacobian matrix solutions. Way to avoid component interference, which is divided into three types, is proposed. The combination of design parameters is decided by comparing the characteristics of area of movement, resolution and velocity. The working space is then shown. The singularity is analyzed by evaluating determinants of the Jacobian matrix. Lengthening the connecting rods and limiting the range of the end effector rotational angles are effective in avoiding the singular configurations as well as interference. Finally, the developed prototype mechanism is introduced, and its application to tool positioning and machining is described.

Key Words : Robot, Manipulator, Machine Tool, Parallel Mechanism, Kinematics, Interference, Working Space, Singularity

1. Introduction

In recent years, parallel mechanisms have attracted attention as multiple degrees of freedom mechanisms for use in heavy material handling, advanced assembly and machine tools. The authors are developing a vertically fixed, linear actuated parallel mechanism for such applications.

A parallel mechanism is connected by two or more closed loop mechanisms in which the base and the end effector are arranged in parallel⁽¹⁾. A typical such mechanism is called the Stewart Platform (SPF), which has 6 degrees of freedom. This was developed by Stewart in a proposal for a jack device

for tire tests by Gough, and has many possibilities⁽²⁾. The characteristics of a parallel mechanism are shown below⁽³⁾⁻⁽⁵⁾.

(1) It is highly precise because of the equalized actuator error.

(2) It is high power due to the parallel arrangement of actuators.

(3) The calculation of inverse kinematics is easy.

(4) Common mechanical parts can be used for each axis.

(5) The working space is small compared with the size of the body.

Taking advantages of such features, various applications are possible.

Parallel mechanisms are classified into "Telescopic", "Rotary", and "Linear" types according to the drive method between the base and end effector joints⁽⁴⁾. These classifications are used for convenience. The telescopic type, which includes the Stewart Platform, has the simplest kinematics among the 3 types⁽⁵⁾. However, the dynamic characteristics and movable space with this type are disadvantageous, because the actuators themselves move. The rotary type allows a decrease in the number of moving

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Fig. 1 Parallel mechanism with vertically fixed linear actuator

sections by using fixed actuators, and thus obtains high speed and a large movable area^{(6),(7)}. However, the positioning accuracy is disadvantageous due to bending moments that arise at links. The linear type provides high speed, high accuracy, and high output due to a structure in which loads are received with a fixed linear guide⁽⁸⁾⁻⁽¹¹⁾. However, problems are that the kinematics calculations are complicated and a large space is required for the base structure. Actuators horizontal or on an inclination are used with this type of mechanism^{(10),(11)}.

Figure 1 shows a vertically fixed, linear actuated parallel mechanism of the linear type. The first mechanism of this kind that was actuated by cylinders was proposed by Merlet⁽⁸⁾. A characteristic of this mechanism is that the direction unit vectors of each actuator are parallel and independent. This device has several practical advantages:

(1) The vertical arrangement of the actuators makes kinematics easy, because the directions of all drive axes conform to a coordinate axis, which in this report is Z.

(2) The actuators are assumed to be composed of servomotors, ball screws and linear guides. These are widely used in industry, and are superior in terms of cost, reliability, and maintainability.

(3) The space occupied by the main body frame is smaller than in types with a horizontal movable area. Also, the frame substitutes as a safety fence, since the range of movement is inside the frame.

This report gives the kinematics and some motion properties of a parallel mechanism with vertically fixed linear actuators. The kinematics can be calcu-

Fig. 2 Geometry of kinematics

lated easily because the vertical arrangement of the actuators makes the geometry simple. Design parameters are chosen to maintain a balance between the movable area, the motion properties and the interference conditions. Singularity is analyzed on the basis of the evaluating determinant of the Jacobian matrix. The calculated singularity value is applied to the ratio of the occupied area to the entire movable area. Finally, handling and cutting examples for a prototype manipulator having 6 degrees of freedom are shown.

2. Kinematics

2.1 Definition of symbols

The following list and Fig. 2 provide definitions of the symbols that are used in this report.

α, β, γ : attitudes around z, y, x axes, respectively

i : number of actuators

p : vectors from origin to end effector center

R : revolution matrix of end effector

p_{bi} : vectors from origin to base points

r_b : length of p_{bi} (scalar)

${}^h s_i$: vectors from center of end effector to joints

r_e : length of ${}^h s_i$ (scalar)

z_i : unit vectors for connecting rods direction

l_c : length of the connecting rods (scalar)

a : unit vectors from base points to actuator joints

c_i : value of actuator control (scalar)

2.2 Inverse kinematics

The kinematics of the 6 degrees of freedom parallel mechanism with vertically fixed linear actuators is expressed in Eq. (1) from the relationship of the connected joints between a base and an end-effector in Fig. 2^{(12),(13)}.

$$p + R^h s_i - p_{bi} = c_i a + l_c z_i \quad (1)$$

When L_i is the left side.

$$L_i - c_i a = l_c z_i \quad (2)$$

Both sides are squared. The secondary formula for c_i is obtained from $a^2=1$, $z_i^2=1$ and Eq. (2).

$$c_i^2 - 2(L_i \cdot a) c_i + L_i^2 - l_c^2 = 0 \quad (3)$$

Fig. 3 Geometry of kinematics

Equation (3) is obtained by the formula from the solution of the secondary equation.

$$c_i = (\mathbf{L}_i \cdot \mathbf{a}) \pm ((\mathbf{L}_i \cdot \mathbf{a})^2 - \mathbf{L}_i^2 + l_c^2)^{1/2} \quad (4)$$

When $\mathbf{L}_i = (l_{xi}, l_{yi}, l_{zi})$ and $\mathbf{a} = (0, 0, 1)$, Eq. (4) becomes Eq. (5).

$$c_i = l_{zi} \pm (l_c^2 - l_{xi}^2 - l_{yi}^2)^{1/2} \quad (5)$$

Paragraph 2 of Eq. (5) is selected to the negative side, because $c_i < l_{zi}$ is clear from Fig. 2.

2.3 Simple inverse kinematics by geometry

The inverse kinematics of the parallel mechanism with vertically fixed linear actuators may be comprehended directly using geometry. Its control variables are also obtained simply.

In Fig. 3, b_0 is set to the origin $(0, 0, 0)$. The actuator arrangements are set to $b_i(x_{bi}, y_{bi}, 0) (= \mathbf{p}_{bi})$. Joints on linear actuators are set to $b_{ji}(x_{bi}, y_{bi}, c_i)$. The length of the connecting rods is set to l_c . Given this, the joints $e_{ji}(x_{ei}, y_{ei}, z_{ei}) (= \mathbf{p} + \mathbf{R}^h \mathbf{s}_i)$ are decided if one provides a position and an end effector attitude. Therefore points $v_i(x_{ei}, y_{ei}, 0)$, which are unloaded vertically from e_{ji} to a supposed base circle, are obtained. Consequently, c_i can be obtained as Eq. (6) from the relation of the trapezoid $b_i - b_{ji} - e_{ji} - v_i$.

$$c_i = z_{ei} - (l_c^2 - (x_{ei} - x_{bi})^2 - (y_{ei} - y_{bi})^2)^{1/2} \quad (6)$$

2.4 Three degrees of freedom model

When a 3 DoF type equipped with three parallel crank mechanisms is considered, kinematics can be acquired with the same technique as for 6 DoFs. This kinematics is completely the same as Eqs. (5) and (6) except that the number of axes is set to 3.

2.5 Differential kinematics

The differential displacements of an end effector are set to $\delta \mathbf{e} = (\delta \mathbf{p}^T \delta \mathbf{\Omega}^T)^T$. Differential movements of actuators are set to $\delta \mathbf{c} = (\delta c_1 \cdots \delta c_6)^T$. When the sides of Eq. (1) are differentiated, Eq. (7), which is the relation of the differential movements between an end effector and actuators, is obtained.

$$\delta \mathbf{p} + \delta \mathbf{R}^h \mathbf{s}_i + \mathbf{R}^h \delta \mathbf{s}_i - \delta \mathbf{p}_{bi} = \mathbf{a} \delta c_i + c_i \delta \mathbf{a} + \delta l_c \mathbf{z}_i + l_c \delta \mathbf{z}_i. \quad (7)$$

Some constants can be eliminated from Eq. (7) because the third term of the left side and the third

Fig. 4 Three 3 DoF mechanism and its inverse kinematics

term of the right side are elastic components, while the fourth term of the left side and the second term of the right side are constant values. Thus, Eq. (8) is obtained.

$$\delta \mathbf{p} + \delta \mathbf{R}^h \mathbf{s}_i = \mathbf{a} \delta c_i + l_c \delta \mathbf{z}_i \quad (8)$$

The second term of the left side in Eq. (8), which shows the attitude change of an end effector, is modified to give Eq. (9).

$$\begin{aligned} \delta \mathbf{R}^h \mathbf{s}_i &= \mathbf{R}_{\delta \mathbf{\Omega}} \delta \mathbf{R}^h \mathbf{s}_i \\ &= \begin{bmatrix} 0 & -\delta \Omega_z & \delta \Omega_y \\ \delta \Omega_z & 0 & -\delta \Omega_x \\ -\delta \Omega_y & \delta \Omega_x & 0 \end{bmatrix} \mathbf{R}^h \mathbf{s}_i \\ &= \delta \mathbf{\Omega} \times \mathbf{R}^h \mathbf{s}_i \quad (\times \text{outer vector}) \end{aligned} \quad (9)$$

Equation (10) is obtained by taking the inner product with $\mathbf{z}_i$ for both sides of Eq. (8). The second term of the right side in Eq. (8) is eliminated from $\mathbf{z}_i \cdot \delta \mathbf{z}_i = 0$.

$$\begin{aligned} \mathbf{z}_i \cdot \delta \mathbf{p} + \mathbf{z}_i \cdot (\delta \mathbf{\Omega} \times \mathbf{R}^h \mathbf{s}_i) &= \mathbf{z}_i \cdot \mathbf{a} \delta c_i + l_c \mathbf{z}_i \cdot \delta \mathbf{z}_i \\ \mathbf{z}_i \cdot \delta \mathbf{p} + (\mathbf{R}^h \mathbf{s}_i \times \mathbf{z}_i) \cdot \delta \mathbf{\Omega} &= \mathbf{z}_i \cdot \mathbf{a} \delta c_i \end{aligned} \quad (10)$$

Equation (10) can be expressed as Eq. (11) by using 6 by 6 Jacobian matrixes. Equation (10) shows relationship between minute movements of actuators and minute movements of an end effector.

$$\mathbf{J}_1 \delta \mathbf{e} = \mathbf{J}_2 \delta \mathbf{c} \quad (11)$$

where,

$$\mathbf{J}_1 = \begin{bmatrix} \mathbf{z}_1^T (\mathbf{R}^h \mathbf{s}_1 \times \mathbf{z}_1) \\ \vdots \\ \mathbf{z}_6^T (\mathbf{R}^h \mathbf{s}_6 \times \mathbf{z}_6) \end{bmatrix} \quad \mathbf{J}_2 = \begin{bmatrix} \mathbf{z}_1^T \cdot \mathbf{a} \cdots 0 \\ \vdots \\ 0 \cdots \mathbf{z}_6^T \cdot \mathbf{a} \end{bmatrix}$$

Inverse kinematics for velocity gives Eq. (12).

$$\dot{\mathbf{c}} = \mathbf{J}_2^{-1} \mathbf{J}_1 \dot{\mathbf{e}} \quad (12)$$

3. Interferences

3.1 Types of interference

The parts of a parallel mechanism may interfere with each other inside the area of movement. The interference of the mechanism can be classified into the following 3 types.

(a) Interference between connecting rod and actuator (Fig. 5(a))

(b) Interference between neighboring connecting rods (Fig. 5(b))

Fig. 5 Types of interference

Fig. 6 Common perpendicular of connecting rods

(c) Interference between connecting rod and end effector (Fig. 5(c))

3.2 Interference between connecting rod and actuator

Type (a) occurs mainly with horizontal movements in the xy direction. When all x, y components of an end effector joint exist in a base joint circle, this interference can be avoided.

$$(\mathbf{p} + \mathbf{R}^h \mathbf{s}_i)_x^2 + (\mathbf{p} + \mathbf{R}^h \mathbf{s}_i)_y^2 < |\mathbf{p}_{bi}|^2 \quad (13)$$

3.3 Interference between neighboring connecting rods

Type (b) occurs mainly with revolution around z axis. This can be avoided if the length of the common perpendicular line between neighboring connecting rods is larger than the diameter of the connecting rods. This interference is also avoided, whether or not the distance of the common perpendicular line of the neighbor connecting rods i, j is larger than the connecting rod diameter, if the intersection points do not exist simultaneously on the connecting rods.

The unit vector of the adjacent connecting rod is set to $\mathbf{z}_i$ and $\mathbf{z}_j$. The unit vector of the common perpendicular line is set to $\mathbf{n}$, and its distance is set to k . The vector from the cross point to the connecting rod is set to $\mathbf{t}_i$ and $\mathbf{t}_j$. The distance from the actuator joint to the cross point is set to p_i and p_j . Then, the following relations are obtained and shown in Fig. 6.

$$\mathbf{n} = (\mathbf{z}_i \times \mathbf{z}_j) / |\mathbf{z}_i \times \mathbf{z}_j| \quad (14)$$

$$\mathbf{z}_i \cdot \mathbf{n} = 0 \quad \mathbf{z}_j \cdot \mathbf{n} = 0 \quad (15)$$

$$\mathbf{t}_i = \mathbf{p}_{bi} + c_i \mathbf{a} + p_i \mathbf{z}_i \quad (16)$$

Fig. 7 Interference between connecting rods and end effector

Fig. 8 Working space volume related with link parameters

$$\mathbf{t}_j = \mathbf{p}_{bj} + c_j \mathbf{a} + p_j \mathbf{z}_j \quad (17)$$

$$\mathbf{k}\mathbf{n} = \mathbf{t}_j - \mathbf{t}_i \quad (18)$$

When these are arranged, p_i and p_j are given.

$$p_i = c_i \{ (\mathbf{p}_{bi} - \mathbf{p}_{bj}) / (c_j - c_i) - \mathbf{a} \} \cdot \mathbf{z}_i \quad (19)$$

$$p_j = c_j \{ (\mathbf{p}_{bi} - \mathbf{p}_{bj}) / (c_j - c_i) - \mathbf{a} \} \cdot \mathbf{z}_j \quad (20)$$

Moreover, the length k of the common perpendicular line serves as the following formula.

$$k = \mathbf{n} \cdot (\mathbf{p}_{bj} + c_j \mathbf{a} - \mathbf{p}_{bi} - c_i \mathbf{a}) \quad (21)$$

Therefore, the conditions of avoidable interference are that does not fill $0 < p_i < l_c$ and $0 < p_j < l_c$ simultaneously, or that fills them simultaneously and k is larger than the connecting rod diameter l_a .

3.4 Interference between connecting rod and end effector

Type (c) occurs mainly with the revolution around the x, y axis. It can be avoided if the inner product between unit vector $\mathbf{z}_i$ and unit vector $\mathbf{e}_p$, which is the direction of the tool, is $\pi/2$ or less.

$$(\mathbf{e}_p \cdot \mathbf{z}_1 > 0) \cap \dots \cap (\mathbf{e}_p \cdot \mathbf{z}_6 > 0) \quad (22)$$

4. Working Space

4.1 Decision of design parameters

To evaluate the properties of a parallel mechanism with vertically fixed linear actuators, 3 constants in Eq. (1) must be decided: the base joint circle radius (r_b), the end effector joint circle radius (r_e), and the connecting rod length (l_c). Figure 8 shows the change in working space with changes in l_c , r_e and r_b . Where, if the base offset angle is 0.2(rad.), end effector side is 0.6(rad.), r_b is 450(mm), and maximum c is 450(mm) then the attitude of the end effector does not

Fig. 9 Resolution and speed related with link parameters

change. According to Fig.8, the working space becomes so large that l_c is long, and has a peak to r_e . The plot in the figure corresponds to the simulation and experimental model, which are mentioned later.

Figure 9 shows the horizontal relation between resolution and speed at an end effector in the center of the working space. According to Figs.8 and 9, the connecting rod length is proportional to the working space and speed, but it is in inverse proportion to resolution.

Thus, selecting design parameters from within the white line linked by the peaks of the contour line in Fig. 8 is the most efficient for maximization of the working space. Enhancing connecting rod length is beneficial for the proportion for working space and speed, but disadvantageous for resolution. Selecting in the upper right part of Fig.8 helps speed and working space, while the lower left part is better for resolution. The easy adjustment of mechanical properties is an advantage of a parallel mechanism.

The design parameters for a computer simulation are selected as $r_e/r_b=0.33$, $l_c/r_b=1.33$ with reference to Figs. 8 and 9. The r_b is selected at 450(mm) due to the restrictions of the place of the installation of the prototype. Therefore, they are as shown in Table 1.

4.2 Working space

Figure 10 shows the appearance of the working space using the design parameters in Table 1. When the attitude of the end effector does not rotate, the appearance of the working space looks like an intermediate form between a cone and 6 pyramids.

4.3 Effect of end effector on attitude

Figure 11 shows the volume change when the attitude is changed around each axis. The working space becomes small as the attitude change is enlarged.

5. Singularity

5.1 Types of singularity

Parallel mechanisms have singularity in the working space. This has been especially reported with

Table 1 Design parameters for simulation

Radius of imaginary base circle	r_b	450 mm
Radius of end effector circle	r_e	150 mm
Connecting rods length	l_c	600 mm

Fig. 10 Working space

Fig. 11 Working space volume related with end effector orientation

SPF⁽¹⁴⁾⁻⁽¹⁶⁾. The singularity can be classified into two categories according to its characteristic⁽³⁾. One of these is in common with serial linkages. This singularity is a lost motion in some directions. The other is unique to parallel mechanisms. This is a loss of force and/or moment in some directions.

5.2 Common singularity to a serial mechanism

When it is qualitatively interpreted that the right side of Eq. (11) becomes 0, the singularity is the loss of motion of an end effector. In this case, certain diagonal elements of a Jacobian J_2 in Eq. (11) may become 0. This means that some angles between a connecting rod and an actuator are $\pi/2$. This is shown in Fig. 12. Equation (3) is a secondary formula of the control value equal to the formula that asks for an intersection in case the distance from the arbitrary points to the actuator line becomes a constant value, the connection rod length. When there is only one solution to Eq. (4), this conforms to the singularity

Fig. 12 Singular configuration in serial linkages

common to serial mechanisms. To avoid this singularity, it is found directly from this figure that enlarge the connecting rod in comparison to the arrangement interval of the linear actuators is effective.

5.3 Unique singularity to parallel mechanisms

When we qualitatively interpret that the left side of Eq. (11) becomes 0, the singularity is the loss of some output of an end effector. This singularity must be avoided because actuators are in danger of destruction by infinite demand outputs. This singularity is examined by the determinant of matrix J_1 in Eq. (11). Calculating $\det J_1$ by scanning an arbitrary xy plane is done to evaluate the singularity, when an optional attitude of an end effector is given. In actual calculation, the xy plane is set to $z=200(\text{mm})$ that is near the center of working space. Figure 13(a), (b) shows the distribution of $\det J_1$ at $(\alpha, \beta, \gamma)=(0, 0, 0)$, $(\alpha, \beta, \gamma)=(4/\pi, 4/\pi, 4/\pi)$.

The center neighborhood in Fig.13(a) corresponds to an area of high manipulability. In Fig. 13 (b), the boundary line between positive and negative determinant values is a set of the singular points. However, the arm motion must be avoided in the $\det J_1 \leq 0$ range, because continuation of movement is necessary in actual control. Therefore, in this report, we define and analyze the evaluated value, the area ratio of the singularity to the movable area in an xy plane.

Figure 14 shows a change of the area ratio of singularity, when changing the attitude of the end effector around x -axis. The area of singularity occurs when the attitude angle around x -axis is larger than about 0.7(rad.). It becomes large with attitude angle of the end effector.

Figure 15 shows the changes in the singularity ratio at $(\alpha, \beta, \gamma)=(4/\pi, 4/\pi, 4/\pi)$, when the length of connecting rods is changing. This figure shows that longer connecting rods are effective in avoiding this singularity. However, an overall design including resolution and working space is necessary, because lengthened connecting rods degrade resolution.

Figure 16 shows a motion example in the area

(a) $(\alpha, \beta, \gamma)=(0, 0, 0)$ (b) $(\alpha, \beta, \gamma)=(4/\pi, 4/\pi, 4/\pi)$ Fig. 13 Distribution of $\det J_1$

Fig. 14 Ratio of singular to movable area related with end-effector rotation

next to this singularity. The end effector face and some faces that were surrounded by 2 connecting rods approach in parallel.

6. Experiment and Application

6.1 Mechanism of prototype

We performed handling and machining experiments using a prototype 6 degrees of freedom manipulator that was made based on the aforementioned

Fig. 15 Ratio of singular to movable area related with link parameters

Fig. 16 Singular configuration in parallel linkages

analysis. The connecting rod length of the prototype was 720 mm ($l_c/r_b=1.6$) in order to avoid singularity and place priority on working space and speed. With these parameters, the horizontal speed at the center of the working space was 1 528 mm/s. The appearance and specifications of the prototype are shown in Fig. 17 and Table 2.

In the actual manufacture of a parallel mechanism, selection of a ball bearing is often a problem. Many practically used ball bearings have a small rocking angle of less than 0.5(rad.). Moreover, mechanical backlash may occur with the passage of time. This machine uses the ball bearing that combines a double angular bearing and universal joint incorporating needles, as shown in Fig. 18. The static elastic limit of the crossing part of a universal joint was 32(kN) at the actual test. The static moment ability of the double angular bearing is 94.1(N-m). When the working weight is assumed to be about 10(kg), these both have sufficient rigidity.

6.2 Control

We made the control system into a position control that is a semi-closed loop feed back system between a motor and a motor-driver, using a personal computer (486 DX2 66 MHz). The calculation time of inverse kinematics was about 85 (microsecond). Figure 19 is a block diagram of this. PTP control is used. The pick-and-place work ordered by positions

Table 2 Design parameters of prototype

Radius of imaginary base joint circle	450 mm
Radius of end effector joint circle	150 mm
Connecting rods length (adjustable)	720 mm
Actuator stroke	400 mm
Screw lead	20 mm
Servo motor	100W AC
Resolution of actuator	0.02 mm
Maximum speed of actuator	1000 mm/s
Payload (without tilt, at center)	10 kg

Fig. 17 Full view of 6-DOF prototype manipulator

Fig. 18 Three-degree of freedom joint

Fig. 19 Block diagram

is realized by PTP control. Straight-line motion and circle motions are also realized by CP control.

6.3 Application for material handling

A work-handling experiment was carried out successfully with a 3-nail zipper. Figure 14 shows the work-handling with tilt.

6.4 Application to machining with low cost

We applied this mechanism to a five-axis machining center. This mechanism allowed machining opera-

Table 3 Specifications of machining experiments

spindle	2400 rpm	
tool	for surface milling	8mm end mill
	for character line milling	8mm ball mill
	for under-cut milling	6mm ball mill
work	mixing paraffine wax

Fig. 20 Work-handling experiment (two exposures)

Fig. 21 Machining experiment. (Upper) Tilt milling for under-cutting. (Lower) Result of the character line milling

tions such as curved surface milling or under-cutting at low cost. The machining experiment was conducted by the specification of Table 3. Figure 21 shows the application to machining with 6 degrees of freedom. This method is effective in the removal of material in the nooks of dies. Figure 21 shows the result of the under-cutting and the character line milling.

7. Conclusion

This report analyzes the kinematics and shows applications for the prototype of a 6 degrees of freedom parallel mechanism with vertically fixed linear actuators.

(1) The inverse and differential kinematics were studied. The inverse kinematics could be obtained directly and easily according to the geometry of a vertical arrangement of linear actuators.

(2) Three kinds of mechanical interference were shown, as were ways to avoid them.

(3) Properties, working space, resolution, and velocity are adjusted by changing the combination of design parameters. Parameters were selected to optimize. However, a change in attitude changes many other characteristics.

(4) The singularity of this mechanism was evaluated with a guideline using the ratio of the area of singularity to area of movement in an arbitrary xy plane. Restricting the attitude of the end effector and lengthening the connecting rods are effective ways to avoid singularity.

(5) A prototype demonstrated that it can be applied to handling work and a machine tool.

In the future, we want to propose calculation techniques for the optimum design.

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References

- (1) Tsusaka, Y., Fukuzumi, T. and Inoue, H., Parallel Manipulator: Its Design and Mechanical Characteristics, JRSJ, (in Japanese), Vol. 5, No. 3 (1987), pp. 180-188.
- (2) Stewart, D., A Platform with Six Degrees of Freedom, Proc. Inst. Mech. Eng., Vol. 180, No. 15 (1965), pp. 371-386.
- (3) Special Issue: Parallel Mechanism, JRSJ, (in Japanese), Vol. 10, No. 6 (1992), pp. 695-769
- (4) Nikkei Mechanical, (in Japanese), No. 450 (1995), pp. 26-49.
- (5) Mechanical design, (in Japanese), Vol. 40, No. 10 (1996), pp. 17-65.
- (6) Uchiyama, M., Imura, K., Tarao, S., Pierrot, F. and Toyama, O., Development of a 6-DOF High-speed Parallel Robot HEXA, JRSJ, (in Japanese), Vol. 12, No. 3 (1994), pp. 117-124.
- (7) Clavel, R., DELTA, A Fast Robot with Parallel Geometry, Proc. Int. Symposium on Industrial Robots, (1988), pp. 91-100.
- (8) Merlet, J.-P. and Gosselin, C., Nouvelle Architec-

- ture Pour un Manipulateur Parallèle a Six Degrés de Liberté, *Mech. Mach. Theory*, (in French), Vol. 26, No. 1 (1991), pp. 77-90.
- (9) Arai, T., Tanikawa, T., Merlet, J.-P. and Sendai, T., Development of a New Parallel Manipulator with Fixed Linear Actuator, *Japan/USA Symposium on Flexible Automation*, Vol. 1 (1996), pp. 145-149.
 - (10) Sato, M., Japanese Patent, (in Japanese), Examined Application File No. 7-54418, (1995).
 - (11) Toyama, T., Japanese Patent, (in Japanese), Unexamined Application File No. 8-150526, (1996).
 - (12) Arai, T., Analysis and Synthesis of a Parallel Link Manipulator Based on its Statics, *JRSJ*, (in Japanese), Vol. 10, No. 4 (1992), pp. 526-533.
 - (13) Ropponen, T. and Arai, T., Accuracy Analysis of a Modified Stewart Platform Manipulator, *Proc. IEEE Int. Conference on Robotics and Automation*, (1995), pp. 521-525.
 - (14) Sugimoto, K., On the Singular Point of Mechanisms, *JRSJ*, (in Japanese), Vol. 11, No. 4 (1993), pp. 550-556.
 - (15) Takeda, Y. and Funahashi, H., Kinematic and Static Characteristics of In-parallel Actuated Manipulators at Singular Points and in Their Neighborhoods, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 60, No. 570, C (1994), pp. 701-708.
 - (16) St-ongue, B.M. and Gosselin, C., Singularity Analysis and Representation of Spatial Six-dof Parallel Manipulators, *Recent Advances in Robot Kinematics*, (1996), pp. 389-398.
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