Study on Development of a machining robot using Parallel mechanism

Kun-Woo Park *, Tae_Sung Kim*, Min-Ki Lee* and Jin-Ho Kyung**
* School of Mechatronic Engineering, Changwon Nat'l University, Changwon, Korea
(Tel : +82-55-275-7553; E-mail: kwoopark@sarim.changwon.ac.kr)
** Robot & Control Group, Intelligence & Precision Machine Dept.,Korea Institute of Macinery and Materials,171, Jang-dong, Yusong-gu, Daejeon
(Tel : +82-42-868-7885; E-mail: jhkyung@kimm.kre.kr)

Abstract: This research develops the robot for the machining work. For machining work(cutting, milling, grilling, etc.), a robot manipulator is constructed by combining a parallel and a serial mechanism to increase stiffness as well as enlarge workspace. Based on the geometric constraints, this paper develops the formulation for inverse/direct kinematics and Jacobian to design and control a robot. Workspace is also analyzed to prove the advantage of the proposed robot.

Keywords: Parallel mechanism, machining work, Kinematics, Jacobian, Workspace

1. INTRODUCTION

In industry, the machining tools with three orthogonal actuators are used to do the machining work. However, these are able to apply to plain work, not to complex 3D work because of lack of d.o.f.. Many researchers make a lot of effort to the application of high d.o.f robot in machining work such as cutting, milling, grilling, etc. However, this kind of work requires robot to have high stiffness, which cannot be provided by conventional serial robot owing to the cantilever structure. Since Stewart-Gough[1] introduced a parallel actuated manipulator, the parallel manipulator is alternative to the stiffness dilemma with high ratio of rigidity to weight. In machining work researches applied to the parallel robot which are HexaM[2], Hexaglide[3], Eclipse[4], etc.. Almost researches study on the fully parallel robot with six actuators connecting the base to the platform. However the major drawbacks of the parallel manipulators are the limited workspace.

We propose the Parallel Mechanism-Wrist Mechanism (PAWM) robot designed by compounding Parallel Mechanism (PM) with serial Wrist Mechanism. The PM with three linear actuators and central axis generates the positional workspace and the WM with three rotary actuators generates the orientational workspace, independently.

This paper develops the formulation for inverse/forward kinematics and Jacobian to be implemented in position and velocity controls. Workspace and singularity loci are also analyzed to prove the advantage of the proposed robot.

2. PARALLEL MEC ANISM- WRIST MEC ANISM (PMWM) RO OT

The PMWM Robot is made up of a PM generating the positional workspace and the WM generating the orientational workspace as shown in Fig. 1. The PM with linear actuation places a movable platform (platform) at a desired position by three linear actuators (LA_i, i=1,2,3) attached to a stationary base (base). Linear actuators, LA_i for i=1,2,3, are attached to B_i through spherical joints and connected to P_i through universal joints establishing link trains, which joint variables are represented by θ_{ij} for j=1,2,..,6 (see Fig.2). Five rotary joints are passive but only one prismatic joint is active to extend or shorten the length of a linear actuator. Points B_i and P_i for i=1,2,3, are affixed symmetrically 120° apart to the base and the platform, respectively, with $\|\overrightarrow{O_0B_i}\|$ =r_B , $\|\overrightarrow{O_3P_i}\|$=$r_P$. Points O_i for i=0,3 are the central points of the base and the platform, respectively. Purpose of a central axis, possessing one prismatic and two universal joints (see Fig. 2), is to constrain the PM permitting its d.o.f., i.e., three in the PM. Adding the WM with three rotary actuator on the platform makes the PMWM to have six d.o.f..

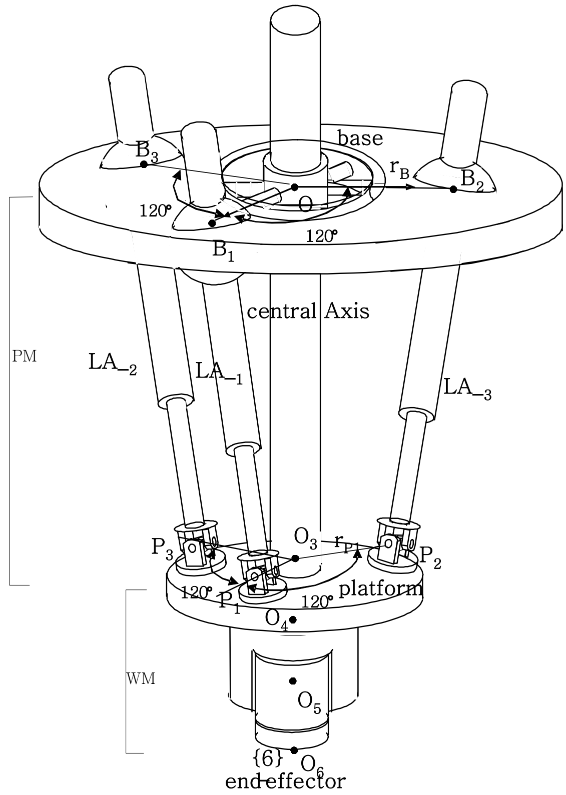


Fig. 1 PMWM Robot Manipulator

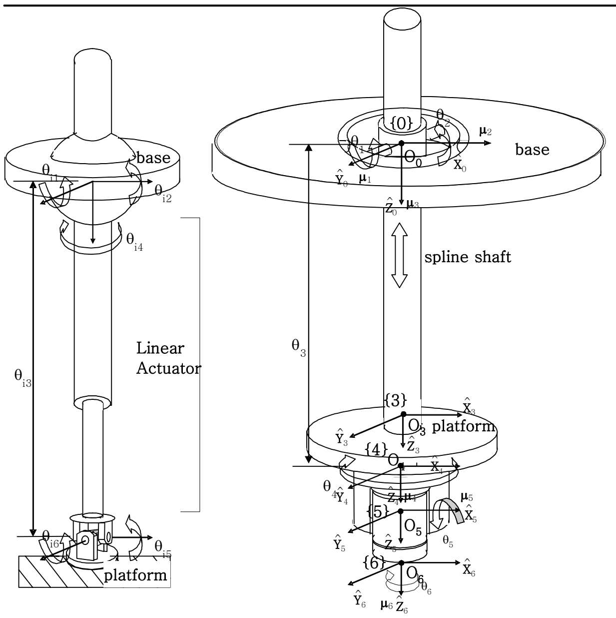


Fig.2 linear actuator and Central axis

3. Kinematics, Jacobian and Workspace Analysis of PMWM

3.1 Kinematics Analysis

Inverse kinematics of the PMWM is formulated to find active joint displacements for a given pose (a position and orientation) of tool. As shown in Fig. 2, frames {0} assigned to the base, {3} and {4} to platform, and {5} and {6} to the WM and tool, with their origins at O_i for i=0,3,4,5,6: the z-axis of frame {0}, Z_o, is downward being perpendicular to the base, the x-axis, X_o, is aligned with μ_1, and the y-axis, Y_o, is determined by a right hand rule, and the other three axes, Z_i, Y_i, Z_i for i=4,5,6, are the same directions as those of the frame {0} at a zero position, i.e., θ_i =0 for i=1,2,..,6.

When the position vector from point O_0 to O_6, $\overrightarrow{O_0O_6}$, and the orientation of frame {6} with respect to {0}, ${}^0R_6$, are given, θ_i for i=1,2,..,6 can be calculated by the following equations :

$$[\theta_1\,\theta_2\,\theta_3\,\theta_4\,\theta_5\,\theta_6\,]^T = K_c^{-1}(\overrightarrow{O_0O_6}, {}^0R_6) \tag{1}$$

where $K_c^{-1}()$ is the inverse kinematics function of the central axis similar to a serial robot. θ_1, θ_2 and θ_3 are passive joints generating by three active joint θ_{i3} of each LA_i. For the closed loops $O_0B_i\ P_i\ O_3$ for i=1,2,3 in the PM, $\overrightarrow{B_iP_i}$, is described by θ_{i1}, θ_{i2} and θ_{i3}, $\overrightarrow{O_0O_3}$ and ${}^0R_3$ are represented by θ_1, θ_2 and θ_3. Referring to (1), we have

$$\|\overrightarrow{B_iP_i}\| = \|\overrightarrow{O_0O_3} - \overrightarrow{O_0B_i} + {}^0R_3\,\overrightarrow{O_3P_i}\| \quad (i=1, 2, 3) \tag{2}$$

The direct kinematics is formulated to find a pose (a position and orientation) of tool for a given active joint displacements. Since the equations (2) are expressed in implicit forms, θ_i for i=1, .. , 6 are obtained by Newton's numerical method.

3.2 Jacobian

For the fully parallel mechanism, Stewart-Gough platform, the Jacobian mapping 6×1 velocities of tool to six active joints velocities can be derived using screw theory or Plucker coordinate[5].
However these cannot be directly applied to the PMWM since velocities are separately generated by the PM and the WM.
Instead, in this paper we use a motor vector defined by the relationship between the velocity of a joint and the resultant velocity of the platform.
If the velocity of point "o" in the platform is $[\Omega\ V]^T$ generated by a unit velocity of joint θ_{ij}, then a 6×1 motor vector is defined as

$$M_{ij} = [\Omega\ V]^T.$$

From the motor algebra [6], a velocity of platform, $V_{platform}$ can be expressed by a linear combination of motors in link trains:

$$V_{platform} = \dot{\theta}_{i1} M_{i1} + \dot{\theta}_{i2} M_{i2} + \cdots + \dot{\theta}_{ik} M_{ik} \quad (i = 1,...n) \tag{3}$$

where n and k is the number of link train and joint, respectively.
For six joints of a central axis and WM, velocity of tool, V_{O_6}, is

$$V_{O_6} = \dot{\theta}_1 M_{c1} + \dot{\theta}_2 M_{c2} + \cdots + \dot{\theta}_6 M_{c6} \tag{4}$$

where M_{ci}(i=1,...,6) is a motor vector between tool and joints of central axis. Form equ. (4), if a given velocity of tool, V_{O_6}, we can get

$$\dot{\Theta} = J_c^{-1} 1 V_{O_6} \tag{5}$$

where $J_c = [M_{c1}\ M_{c2} \cdots M_{c6}]^T$, $\dot{\Theta} = [\dot{\theta}_1\ \dot{\theta}_2\ \dot{\theta}_3\ \dot{\theta}_4\ \dot{\theta}_5\ \dot{\theta}_6]^T$. Velocities $\dot{\theta}_4$, $\dot{\theta}_5$ and $\dot{\theta}_6$ are directly controlled by the active rotary joint of WM but $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{\theta}_3$ must be indirectly generated by three active joints of LA_i of PM. To compute active joints velocities of LA_i, the velocity of point "O_4" in the platform is calculated by following equation:

$$V_{O_4} = \dot{\theta}_1\, {}^{O_4}M_{c1} + \dot{\theta}_2\, {}^{O_4}M_{c2} + \dot{\theta}_3\, {}^{O_4}M_{c3} \tag{6}$$

where ${}^{O_4}M_{ci}$ (i=1, 2, 3) is a 6×1 motor vector between O_4 and joint θ_i. From equ. (6), we can get

$$V_{O_4} = {}^{O_4}J_c\ \dot{\Theta}_c \tag{7}$$

where ${}^{O_4}J_c$ =[${}^{O_4}M_{c1}$ ${}^{O_4}M_{c2}$ ${}^{O_4}M_{c3}$]^T, $\dot{\Theta}_c$ =[$\dot{\theta}_1$ $\dot{\theta}_2$ $\dot{\theta}_3$]^T. For a given, V_{O_4} a set of joint rates of *i*th active link train is acquired by

$$[\dot{\theta}_{i1}\ \dot{\theta}_{i2} \cdots\ \dot{\theta}_{i6}]^T = {}^{O_4}J_i^{-1}\ V_{O_4} \tag{8}$$

where ${}^{O_4}J_i$ =[${}^{O_4}M_{i1}$ ${}^{O_4}M_{i2}$ $\cdots$ ${}^{O_4}M_{i6}$]^T (i = 1,2,3) is motor vector between O_4 and θ_{ij} of the LA_i.

If ${}^{O_4}J_i^{-1}$ =[S_{i1} S_{i2} $\cdots$ S_{i6}]^T, velocities of active joints, $\dot{\theta}_{i3}$, is

$$\dot{\theta}_{i3} = S_{i3}\ V_{O_4} \tag{9}$$

Combining (6), (8) and (9) yields

$$[\dot{\theta}_{13}\ \dot{\theta}_{23}\ \dot{\theta}_{33}\ \dot{\theta}_4\ \dot{\theta}_5\ \dot{\theta}_6]^T = \mathrm{AB}\ J_c^{-1}\ V_{O_6} \tag{10}$$

where A and B are 6×21 and 21×6 matrices, respectively, as shown following :

$$A=\begin{bmatrix} S_{13} & & & & & \\ & S_{23} & & 0 & & \\ & & S_{33} & & & \\ & & & 1 & & \\ & 0 & & & 1 & \\ & & & & & 1 \end{bmatrix}, B=\begin{bmatrix} {}^{O_4}M_{c1} & & & & \\ {}^{O_4}M_{c2} & & 0 & & \\ {}^{O_4}M_{c3} & & & & \\ & 1 & & & \\ 0 & & 1 & & \\ & & & & 1 \end{bmatrix}$$

Therefore, a 6×6 Jacobian matrix is

$$\mathrm{J} = \mathrm{A\ B}\ J_c^{-1} \tag{11}$$

Based on the virtual work principle, the Jacobian with respect to linear actuators and force/moment is

$$\begin{bmatrix} \\ N \end{bmatrix} = J^T \begin{bmatrix} \tau_1 \\ \vdots \\ \tau_6 \end{bmatrix} \tag{12}$$

where F and N are the force and moment of the tool, and τ_i(i=1,..,6) is motor torques of linear actuators and rotary actuators.

In this paper, we apply the Jacobian for velocity control and singularity analysis.

3.3 Workspace Analysis

The workspace is decoupled into two: One is the positional workspace generated by the PM and the other is the orientational workspace by the WM. The orientational workspace is directly generated by three active joints on the WM. However, the positional workspace is complicated by being generated by three LA_i and a central axis. This paper analyzes only positional workspace.

The positional workspace is formed by the trajectory described by point O_3 on the platform, when LA_i for i=1, 2, 3, with minimum or maximum extension, are rotated about their fixed joint-located at point B_i. With $\{x,y,z\}^T = \overrightarrow{O_0O_3}$, $\{x_{0i}, y_{0i}, z_{0i}\}^T = \overrightarrow{O_0B_i} - {}^0R_3\ \overrightarrow{O_3P_i}$ " , From equ. (2), θ_{i3}^2 is written as

$$\theta_{i3}^2 = (x-x_{0i})^2+(y-y_{0i})^2+(z-z_{0i})^2 \qquad (i=1, 2, 3) \tag{13}$$

When LA_i$_{min}$ ≤ θ_{i3}^2 ≤ LA_i$_{max}$, substituting the minimum and the maximum lengths into (13) gives the concentric spheres of radii LA_i$_{min}$ and LA_i$_{max}$, respectively. The workspace in 3D Cartesian space can be described as the intersection of three regions. Using the method addressed by Gosselin [7], we dissect the workspace volume into sections.

4. CONSTRUCT OF T E PMWM

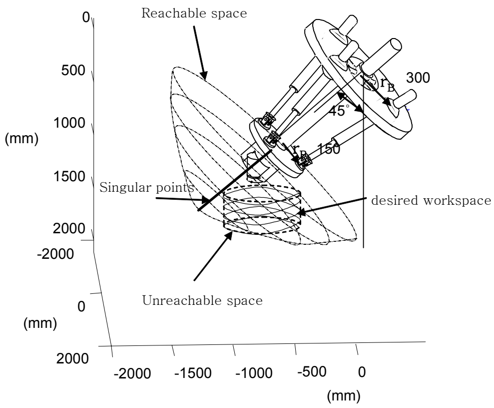
We design the PMWM which has a desired Φ600-400H (mm) cylindrical workspace and has simultaneously not singular points into workspace using analysis of kinematics, Jacobian, and workspace for three cases shown as Table I.

If the initial configuration of the PMWM has the base and the platform perpendicular to WM, i.e., θ_4=0, the Jacobian is not invertible and singularity, i.e., det(J)=0. To avoid singularity, we have setting initial configuration at which the base and the WM have -45° and 0° about the working plain, respectively, i.e., θ_4=45, shown as Fig. 3.

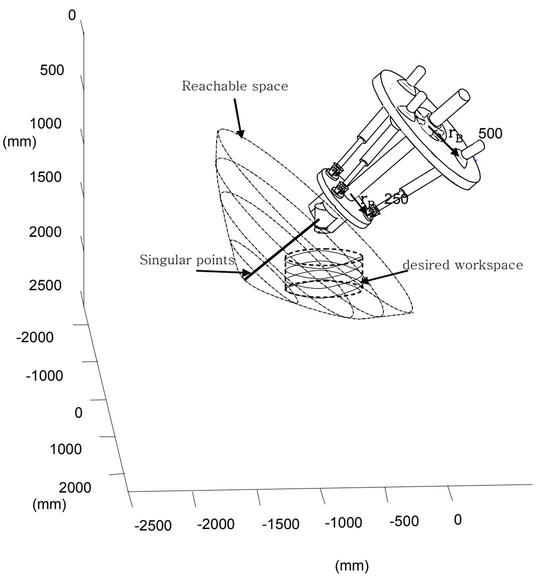
Table I. Design parameters of the PMWM robot

parameters(mm)	Case I	Case II	Case III
radius of base(r_B)	300	500	500
radius of base(r_P)	150	250	250
LA_i$_{min}$	600	900	1200
LA_i$_{max}$	1400	1700	2000

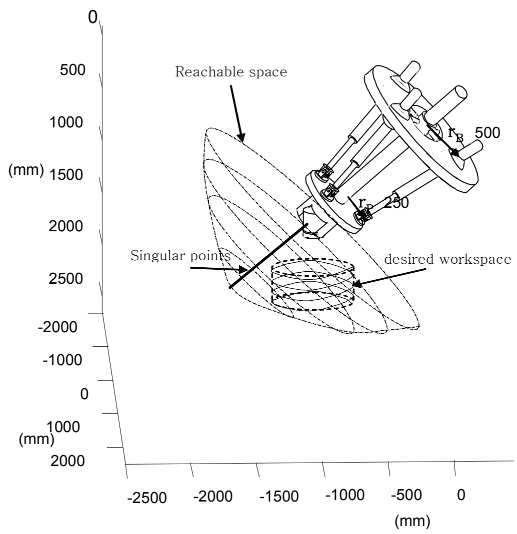
Fig. 3 shows the positional workspace of the PMWM with singularity points. Both case II and case III meet the desired workspace but case I does not because of unreachable space.



a) Workspace of case I



b) Workspace of case II



c) Workspace of case III

Fig. 3 Results of workspace analysis

Fig. 4 shows motors torques of linear actuators and rotary actuators when the PMWM robot is moved a screw motion through the desired workspace and the normal force, 10kN, is acting at tool for Case II and III. Motors torques of case II are 24% less than those of case III.

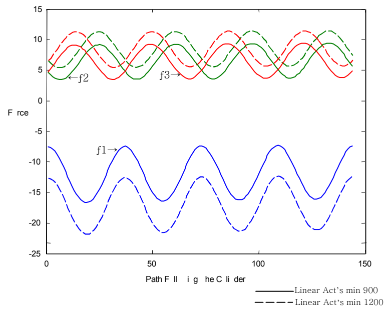
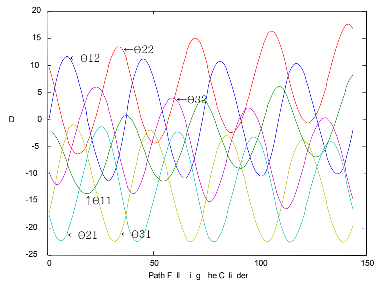
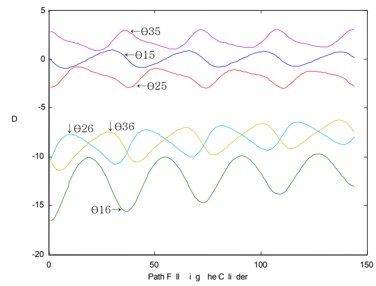


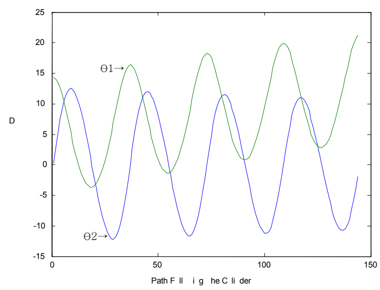
Fig. 4 Motor torques



a) Motion of joint θ_{i1}, θ_{i2} and θ_{i3}



b) Motion of joint θ_{i5} and θ_{i6}



c) Motion of joint θ_1, θ_2 and θ_3

Fig. 5 Motions of spherical and universal joints in central axis and LA_i in Case II

When the PMWM robot is moved a screw motion through the desired workspace, Fig. 5 shows that motions of spherical and universal joints in PM are -25 ° ¯ 25 ° .

At the results we choose design parameters for the PMWM robot, as shown in Table II.

Table II. Spec. of Central Axis, Linear actuator and Joints for the PMWM robot

parameters	Spec.
radius of base(r_B)	500mm
radius of base(r_P)	250mm
LA_i_{min}	900mm
LA_i_{max}	1700mm
Stroke of linear actuator	800mm
Ranges of joint θ_{i1}, θ_{i2} and θ_{i3}	-25 ° ¯ 25 °
Ranges of joint θ_{i5} and θ_{i6}	-20 ° ¯ 20 °
Ranges of joint θ_1, θ_2 and θ_3	-25 ° ¯ 25 °

5. CONCLUSION

This paper designs the PMWM robot for the machining work. The proposed PMWM is consisted of PM and WM generating a positional and orientational workspace, respectively. The PMWM has some advantages of follows:

1) The PM has a high stiffness standing a payload.
2) The WM has a large orientational workspace
3) The PMWM has a central axis constraining the PM permitting its d.o.f.

To design the proposed PMWM robot, we computed kinematics, Jacobian and workspace to decide specifications of a central axis, linear actuators and joints which meet the desired workspace and avoid the singularity into workspace.
In future, we will study on the optimal design and dynamic analysis included gravity, inertial loads and payloads.

ACKNOWLEDGMENTS

This work was supported by the Gyeongnam Technopark and the Ministry of Commerce, Industry and Energy (MOCIE), Korea.

REFERENCES

[1] D. Stewart, "A platform with six degrees of freedom," in Proc. Inst. Mech. Eng., vol. 180, part 1, no. 5, 1965-1966, pp. 371-386.
[2] F. Pierrot, P. Dauchez and A. Fournier, Fast parallel robots. Journal of Robotic Systems, 8(6), pp. 829-840, 1991.
[3] M. Honegger, A. Codourey, and E. Burdet, "Adaptive control of the Hexaglide, a 6 dof parallel manipulator," IEEE int. Conf. on Robotics and Automation, pp. 543-548, Albuquerque, April, 21-28, 1997.
[4] J. Kim and F. C. Park, "Eclipse, A new parallel mechanism prototype," Position paper in Proceedings of the First European-Americna Forum on Parallel Kinematic Machines, Milan, Italy, August 31-September 1, 1998.
[5] E. F. Fichter, "A Stewart Platform-Based Manipulator: General Theory and Practical Construction", Int. J. Robot. Res., vol. 5, pp. 157-182, 1986.
[6] K. Sugimoto, "Kinematic and Dynamic Analysis of Parallel Manipulators by Means of Motor Algebra", ASME J. Mechanisms, Transmission, and Automation in Design, vol. 109, pp. 3-7, Mar, 1987.
[7] C. M. Gosselin, "Determination of the workspace of 6-dof parallel manipulators". ASME J. Mech. Design, vol. 112, pp. 331-336, 1990.