Study on Development of a machining robot using Parallel mechanism

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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 design and control a robot. Workspace is also analyzed to prove the advantage of the proposed robot.

2. PARALLEL MECHANISM-WRIST MECHANISM (PMWM) ROBOT

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 ||O_iB_i||=r_B, ||O_iP_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.
3. Kinematics, Jacobian and Workspace Analysis of PMWM

3.1 Kinematics Analysis

Inverse kinematics of the PMWM 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, $\theta_i$ for $i=1, \ldots, 6$ are obtained by Newton's numerical method.

$$\Theta = J^{-1}_e V_{O_i}$$

where $J_e$ is the direct kinematics function of the central axis similar to a serial robot. $\theta_1, \theta_2$ and $\theta_3$ are passive joints generating by three active joint $\theta_{1i}$ of each LA_i. For the closed loops $O_OB_i P_i O_i$ for $i=1,2,3$ in the PM, $\vec{O}_i P_i$ is described by $\theta_{1i}, \theta_2$ and $\theta_{3i}, \vec{O}_i O_i$ and $\vec{O}_i P_i$ are represented by $\theta_1, \theta_2$ and $\theta_3$.

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, $\theta_i$ for $i=1, \ldots, 6$ are obtained by Newton's numerical method.

$$M_{ij} = [\Omega \cdot V]^T, \quad \Omega = J^{-1}_e V_{O_i}$$

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, $V_{O_i}$, is

$$V_{O_i} = \dot{\theta}_1 M_{i1} + \dot{\theta}_2 M_{i2} \ldots + \dot{\theta}_6 M_{i6} \quad (i = 1, \ldots, n) \quad (3)$$

where $Mc_i (i=1, \ldots, 6)$ is a motor vector between tool and joints of the platform. According to (2), if a given velocity of tool, $V_{O_i}$, we can get

$$\dot{\Theta} = J^{-1}_e V_{O_i}$$

where $J_e = [M_{e1}, M_{e2}, \ldots, M_{e6}]^T$. 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 joint velocities of LA_i, the velocity of point "O_i" in the platform is calculated by following equation:

$$V_{O_i} = \dot{\theta}_1 M_{i1} + \dot{\theta}_2 M_{i2} + \dot{\theta}_3 M_{i3}$$

3.2 Jacobian

For the fully parallel mechanism, Stewart-Gough platform, the Jacobian mapping $6 \times 1$ 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 $[\Omega \cdot V]^T$ generated by a unit velocity of joint $\theta_i$, then a $6 \times 1$ motor vector is defined as

$$M_{ij} = [\Omega \cdot V]^T.$$
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 \( \{x_0, y_0, z_0\} = O_3 \hat{O}_i \), \( \{x_0, y_0, z_0\} = O_3 \hat{O}_i \), the concentric spheres of radii LA_\text{im}_\text{in} and LA_\text{im}_\text{ax}, 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 THE PMWM

We design the PMWM which has a desired \( \Phi \) 600-400H (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., \( \theta_3 = 0 \), the Jacobian is not invertible and singularity, i.e., \( \text{det}(J) = 0 \). 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., \( \theta_3 = 45 \), shown as Fig. 3.
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

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 \(-25^\circ \sim 25^\circ\).

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

<table>
<thead>
<tr>
<th>parameters</th>
<th>Spec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius of base(rB)</td>
<td>500mm</td>
</tr>
<tr>
<td>radius of base(rP)</td>
<td>250mm</td>
</tr>
<tr>
<td>LA ( L_{imin} )</td>
<td>900mm</td>
</tr>
<tr>
<td>LA ( L_{imax} )</td>
<td>1700mm</td>
</tr>
<tr>
<td>Stroke of linear actuator</td>
<td>800mm</td>
</tr>
<tr>
<td>Ranges of joint ( \theta_1 ), ( \theta_2 ) and ( \theta_3 )</td>
<td>(-25^\circ \sim 25^\circ)</td>
</tr>
<tr>
<td>Ranges of joint ( \theta_4 ) and ( \theta_5 )</td>
<td>(-20^\circ \sim 20^\circ)</td>
</tr>
<tr>
<td>Ranges of joint ( \theta_6 ), ( \theta_7 ) and ( \theta_8 )</td>
<td>(-25^\circ \sim 25^\circ)</td>
</tr>
</tbody>
</table>

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.

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