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Design and Kinematics Analysis of a Drilling Robot

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ABSTRACT
This study deals with the design and kinematical analysis of a drilling robot with five degrees of freedom. It has been designed through a three-dimensional CAD program and subjected to static analysis test via the analysis module of the same program. Revolving joints have been used for each linkage. Thanks to robotic arm design, it is aimed at carrying out operations with high sensitivity in which human factor is excluded in automation-weighted assembly lines.

Keywords
Robotics, drilling robots, kinematics of manipulators.

1. INTRODUCTION
The history of industrial automation is characterized by the rapid periods of change in the popular methods [1]. The term “robot” is defined by the Robot Institute of America as "a reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks." [1,2]. The use of industrial robots, first identified in the l960s as unique devices [2,3], along with computer aided design and computed aided manufacturing systems, characterizes the latest trends in the automation of the manufacturing process. While human labor cost increased, robot prices dropped. In the end, robots did not just become cheaper, they became more effective, more accurate and more flexible [2]. It is now undeniable that the robots manufactured under such conditions have an impact on machining and there are required especially in assembly lines. Drilling is one of the most important machining processes carried out as a last operation [4,7]. Drilling process constitutes about one third of all machining operations. It can be compared to the processes of turning and milling in some aspects. However, differently from these processes, chip breaking and evacuation are the processes of critical importance in drilling. As the hole length increases, it becomes increasingly difficult to controlthe process and carry out machining. Chip formation during the drilling process affects cutting forces and temperature, thus also indirectly affecting the surface quality and measurement accuracy. Besides, chip disposability is the another factor that affects the hole quality and it changes depending on the cutting parameters such as speed and feed rate. Cutting speed and feed rate are the most important parameters in drilling. They are the factors that determine the performance of the cutting tools and they directly affect the cutting forces and temperature during the cutting process [5,6,7].

In their study, Sönmez et al. examine the control of a robot with three degrees of freedom. They first calculate the kinematics and inverse kinematics, and they propose an artificial neural network model to control the robot. In the inverse kinematics, the coordinates of the end effector are given as an input [8].

The basic principle of moving a robot is to move the end effector from the base along a path to the target. Such movement changes both the orientation and position of the robot [9,10].

In their study titled “The design and control of a therapeutic exercise robot for lower limb rehabilitation: Physiotherabot”, Adlı et al. presented the design and control of a therapeutic exercise robot with three degrees of freedom. They developed a ‘‘Human–Machine Interface’’ with a rule-based control structure. The robot manipulator they designed learned specific exercise motions as well as performing active and passive exercises without the physiotherapist (PT) through the Human–Machine Interface[11].

2. MECHANICS AND CONTROL OF ROBOTS
Robot kinematics has two areas of concern: the first one is the design of a robot in three dimensional space, and the second one is positioning the objects around it. Positioning can be described with two components: position vector and orientation matrix. Mathematically, positions of objects are described with a position vector and their orientation is described with an orientation matrix [12]. A coordinate system is attached to the center of the object, and its position and orientation in three-dimensional space is described. Figure 1 shows how these coordinate systems are attached. In this way, the relationship between position and orientation in robotic workplaces is described [12].

2.1 Direct Kinematics of Robots
Kinematics is the science that studies and treats motion without regard to the forces which cause it. In the science of kinematics, position, velocity, acceleration and all higher order derivatives of the position variables are studied. Therefore, the kinematics of manipulators refers to all the geometrical and time-based properties of the motion [2].

A robot consists of a set of serial links connected to each other by prismatic or revolute joints from the base frame to the tool frame. The relationship of the adjacent two linkages can be described through a homogeneous transformation matrix. For the consecutive joints, these transformation matrices are multiplied to describe the relationship between the base frame and tool frame. The relationship gives the orientation and position of the tool frame relative to the base frame. We can also say that this relationship gives the orientation and position of intermediate axes relative to the major axes. In other words, inverse kinematicsequations determine the position and orientation of the end effector given the values for the joint variables (prismatic or revolute) of the robot [12]

2.2 Inverse Kinematics of Robots

Given the position and orientation of the end-effector of the manipulator, the problem of inverse kinematics is to calculate all possible sets of joint angles that could be used to attain. It is a fundamental problem in the practical use of manipulators [2]. Figure 2 shows that angles can be calculated using the orientation and position matrices.

Solution of inverse kinematics equations is highly complex, since they are nonlinear. The nonlinear set of equations could produce multiple solutions, instead of a single solution [12].

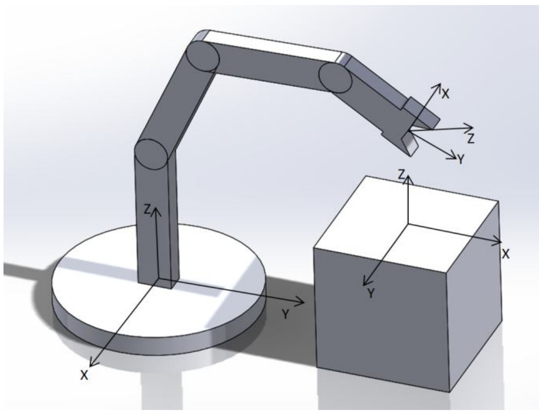

Figure 1. Attachment of a coordinate system to the robot and objects

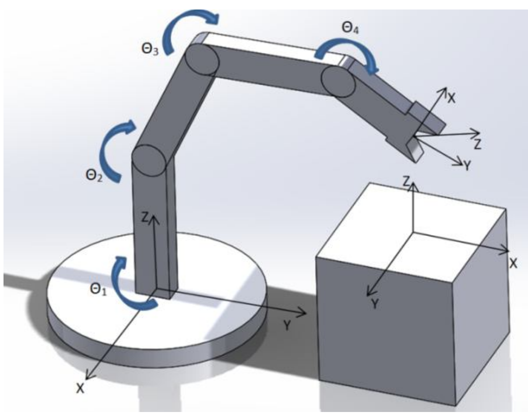

Figure 2. Inverse kinematics can describe the joint angle variables relative to the orientation and position of the end-effector

3. METHOD

In this study, a robot arm for drilling was designed and the kinematic analysis of it was carried out. The robot arm planned to be used especially in automation-based assembly lines is aimed to provide more accurate selection of cutting parameters.

3.1 Design

The robot arm shown in Figure 3 was designed as a manipulator with five degrees of freedom. The body consists of revolute joints. A servo motor with two degrees of freedom was decided to be used in the wrist. The manipulator will be used for drilling particularly plastic and wood products.

The body material will be Al 6063-T1. The reason for preferring aluminum alloy in the design of the manipulator is to increase the functionality by decreasing the weight. Statistical analyses showed that optimum results will be achieved by using this material.

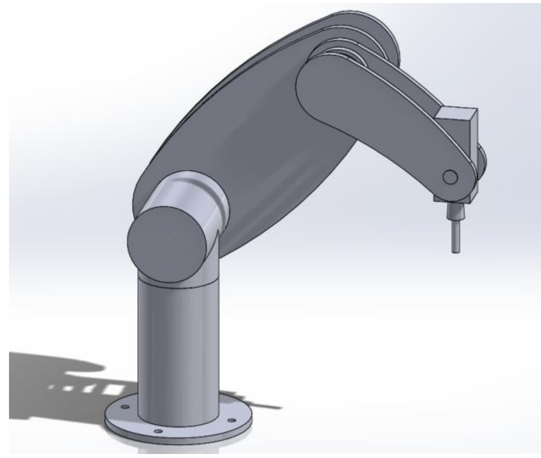

Figure 3. Drilling robot with five degrees of freedom

3.2 Analysis of Kinematics

In the kinematic analysis, the kinematic structure was built using the DenavitHartenberg notation. We studied on a manipulator with 5 degrees of freedom. The system consisted of five rotational joints (5R mechanism). Table 1 shows the DenavitHartenberg parameters that describe the joint.

Table 1.DenavitHartenberg parameters for the joints of the drilling robot

Axis	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	$-\frac{\pi}{2}$	0	0	θ_2
3	0	a2	d3	θ_3
4	$-\frac{\pi}{2}$	a3	d4	θ_4
5	$\frac{\pi}{2}$	0	0	θ_5

We obtained the following main matrix by multiplying the transformation matrix derived by using the Denavit Hartenberg parameters for each joint and departure point shown in Table 1.

.

$$ {}^{0}_{5}T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & P_x \\ r_{21} & r_{22} & r_{23} & P_y \\ r_{31} & r_{32} & r_{33} & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T\,{}^{4}_{5}T \quad (1) $$

We used MATLAB for matrix multiplication. Below are the elements we obtained from transformation matrix multiplication.

$r_{11}=c_5s_1s_4 - c_1(s_5(c_2s_3 + c_3s_2) - c_4c_5(c_2c_3 - s_2s_3))$ (2)

$r_{12}=- c_1(c_5(c_2s_3 + c_3s_2) + c_4s_5(c_2c_3 - s_2s_3)) - s_1s_4s_5$ (3)

$r_{13}=c_1s_4(c_2c_3 - s_2s_3) - c_4s_1$ (4)

$r_{21}=- s_1(s_5(c_2s_3 + c_3s_2) - c_4c_5(c_2c_3 - s_2s_3)) - c_1c_5s_4$ (5)

$r_{22}=c_1s_4s_5 - s_1(c_5(c_2s_3 + c_3s_2) + c_4s_5(c_2c_3 - s_2s_3))$ (6)

$r_{23}=c_1c_4 + s_1s_4(c_2c_3 - s_2s_3)$ (7)

$r_{31}=- s_5(c_2c_3 - s_2s_3) - c_4c_5(c_2s_3 + c_3s_2)$ (8)

$r_{32}=c_4s_5(c_2s_3 + c_3s_2) - c_5(c_2c_3 - s_2s_3)$ (9)

$r_{33}=-s_{23}s_4$ (10)

$P_x=c_1(a_3c_{23}- d_4s_{23}+ a_2c_2) - d_3s_1$ (11)

$P_y=s_1(a_3c_{23}- d_4s_{23}+ a_2c_2) + d_3c_1$ (12)

$P_z=- d_4c_{23}- a_3s_{23}- a_2s_2$ (13)

In doing so, we completed the inverse kinematics.
In the inverse kinematic analysis, angles of each revolute joint were calculated using the main frame matrix.

$$ {}^{B}_{W}T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & P_x \\ r_{21} & r_{22} & r_{23} & P_y \\ r_{31} & r_{32} & r_{33} & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (14) $$

$$ {}^{B}_{W}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T\,{}^{4}_{5}T \quad (15) $$

$$ {}^{0}_{1}T^{-1}\,{}^{B}_{W}T = {}^{1}_{0}T^{-1}\,{}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T\,{}^{4}_{5}T \quad (16) $$

The angle θ_1 is obtained byequating (2,4) in the new transformation matrix:

$\theta_1 = atan2(P_y, P_x) - atan2(d_3, \pm\sqrt{P_x^2 + P_y^2 - d_3^2})$ (17)

If weequate both (1,4) and (3,4) elements in the transformation matrices, we find the angle θ_3:

$\theta_3 = atan2(a_3, d_4) - atan2(K, \pm\sqrt{a_3^2 + d_4^2 - K^2}$(18)

The next step involves using ${}^{0}_{3}T(\theta_2)^{-1} * {}^{0}_{5}T = {}^{3}_{4}T(\theta_4)\,{}^{4}_{5}T(\theta_5)$ to obtain θ_{23}.

$\theta_{23} = atan2[(-a_3 - a_2c_3)P_z - (c_1P_x + s_1P_y)(d_4 - a_2s_3), (a_2s_3 - d_4)P_z - (a_3 + a_2a_3)(c_1P_x + s_1P_y)$(19)

$\theta_{23} - \theta_3 = \theta_2$ (20)

$\theta_4 = atan2(-r_{13}s_1 + r_{23}c_1, -r_{13}c_{23}c_1 - r_{23}c_{23}s_1 + r_{33}s_{23})$(21)

We obtained θ_5 by multiplying $[{}^{0}_{4}T(\theta_4)]^{-1}\,{}^{0}_{5}T = {}^{4}_{5}T(\theta_5)$ matrices.

$c_5 = r_{11}(s_1s_4 + c_1c_2c_3c_4 - c_1c_4s_2s_3) - r_{21}(c_1s_4 - c_2c_3c_4s_1 + c_4s_1s_2s_3) - r_{31}s_{23}c_4$(22)

$s_5 = -r_{31}c_{23} - r_{11}s_{23}c_1 - r_{21}s_{23}$(23)

$\theta_5 = atan2(s_5, c_5)$ (24)

Following rotation matrices were derived from the previously obtained transformation matrices:

$$ \left. \begin{aligned} {}^{1}_{0}R &= \begin{bmatrix} c_1 & s_1 & 0 \\ -s_1 & c_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ {}^{2}_{1}R &= \begin{bmatrix} c_2 & 0 & -s_2 \\ -s_2 & 0 & -c_2 \\ 0 & 1 & 0 \end{bmatrix} \\ {}^{3}_{2}R &= \begin{bmatrix} c_3 & s_3 & 0 \\ -s_3 & c_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ {}^{4}_{3}R &= \begin{bmatrix} c_4 & 0 & -s_4 \\ -s_4 & 0 & -c_4 \\ 0 & 1 & 0 \end{bmatrix} \\ {}^{5}_{4}R &= \begin{bmatrix} c_5 & 0 & s_5 \\ -s_5 & 0 & c_5 \\ 0 & -1 & 0 \end{bmatrix} \end{aligned} \right\} \quad (25) $$

The angular velocity is given by ${}^{i+1}\omega_{i+1} = {}^{i+1}_{i}R\,{}^{i}\omega_i + \dot{\theta}_{i+1}\,{}^{i+1}z_{i+1}$. The linear velocity is given by ${}^{i+1}\nu_{i+1} = {}^{i+1}_{i}R\left({}^{i}\nu_i + {}^{i}\omega_i x\,{}^{i}P_{i+1}\right)$. If we use the data in these equations, we will find:

$$ {}^{1}\omega_1 = {}^{1}_{0}R\,{}^{0}\omega_0 + \dot{\theta}_1\,{}^{1}z_1 = \begin{bmatrix} c_1 & s_1 & 0 \\ -s_1 & c_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} 0 + \dot{\theta}_1 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & \dot{\theta}_1 \end{bmatrix}^T \quad (26) $$

$$ {}^{1}\nu_1 = {}^{1}_{0}R\left({}^{0}\nu_0 + {}^{0}\omega_0 x\, {}^{0}P_1\right) = \begin{bmatrix} c_1 & s_1 & 0 \\ -s_1 & c_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\left(\begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T + 0\right) = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T \tag{27} $$

$$ {}^{2}\omega_2 = {}^{2}_{1}R\,{}^{1}\omega_1 + \dot{\theta}_2\,{}^{2}z_2 = \begin{bmatrix} c_2 & 0 & -s_2 \\ -s_2 & 0 & -c_2 \\ 0 & 1 & 0 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 \end{bmatrix} + \dot{\theta}_2\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} -s_2\dot{\theta}_1 & -c_2\dot{\theta}_1 & \dot{\theta}_2 \end{bmatrix}^T \tag{28} $$

$$ {}^{2}\nu_2 = {}^{2}_{1}R\left({}^{1}\nu_1 + {}^{1}\omega_1 x\, {}^{1}P_2\right) = \begin{bmatrix} c_2 & 0 & -s_2 \\ -s_2 & 0 & -c_2 \\ 0 & 1 & 0 \end{bmatrix}\left(\begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T + \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 \end{bmatrix} x \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}\right) = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T \tag{29} $$

$$ {}^{3}\omega_3 = {}^{3}_{2}R\,{}^{2}\omega_2 + \dot{\theta}_3\,{}^{3}z_3 = \begin{bmatrix} c_3 & s_3 & 0 \\ -s_3 & c_3 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} -s_2\dot{\theta}_1 \\ -c_2\dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} + \dot{\theta}_3\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} -s_{23}\dot{\theta}_1 & -c_{23}\dot{\theta}_1 & \dot{\theta}_2 + \dot{\theta}_3 \end{bmatrix}^T \tag{30} $$

$$ {}^{3}\nu_3 = {}^{3}_{2}R\left({}^{2}\nu_2 + {}^{2}\omega_2 x\, {}^{2}P_3\right) = \begin{bmatrix} c_3 & s_3 & 0 \\ -s_3 & c_3 & 0 \\ 0 & 0 & 1 \end{bmatrix}\left(\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} -s_2\dot{\theta}_1\vec{i} \\ -c_2\dot{\theta}_1\vec{j} \\ \dot{\theta}_2\vec{k} \end{bmatrix}\begin{bmatrix} a_2\vec{i} \\ 0 \\ d_3\vec{k} \end{bmatrix}\right) \tag{31} $$

$$ {}^{3}\nu_3 = {}^{3}_{2}R\left({}^{2}\nu_2 + {}^{2}\omega_2 x\, {}^{2}P_3\right) = \begin{bmatrix} c_3 & s_3 & 0 \\ -s_3 & c_3 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} -s_2\dot{\theta}_1 d_3 \\ \dot{\theta}_2 a_2 + s_2\dot{\theta}_1 d_3 \\ c_2\dot{\theta}_1 a_2 \end{bmatrix} = \begin{bmatrix} -c_3 s_2\dot{\theta}_1 d_3 + s_3(\dot{\theta}_2 a_2 + s_2\dot{\theta}_1 d_3) \\ s_3 s_2\dot{\theta}_1 d_3 + c_3(\dot{\theta}_2 a_2 + s_2\dot{\theta}_1 d_3) \\ c_2\dot{\theta}_1 a_2 \end{bmatrix} \tag{32} $$

$$ {}^{4}\nu_4 = {}^{4}_{3}R\left({}^{3}\nu_3 + {}^{3}\omega_3 x\, {}^{3}P_4\right) = \begin{bmatrix} c_4 & 0 & -s_4 \\ -s_4 & 0 & -c_4 \\ 0 & 1 & 0 \end{bmatrix}\left(\begin{bmatrix} -c_3 s_2\dot{\theta}_1 d_3 + s_3(\dot{\theta}_2 a_2 + s_2\dot{\theta}_1 d_3) \\ s_3 s_2\dot{\theta}_1 d_3 + c_3(\dot{\theta}_2 a_2 + s_2\dot{\theta}_1 d_3) \\ c_2\dot{\theta}_1 a_2 \end{bmatrix} + \begin{bmatrix} -s_{23}\dot{\theta}_1 i \\ -c_{23}\dot{\theta}_1 j \\ (\dot{\theta}_2 + \dot{\theta}_3)k \end{bmatrix}\begin{bmatrix} a_3\vec{i} \\ d_4 \\ 0 \end{bmatrix}\right) \tag{33} $$

$$ {}^{4}\nu_4 = \begin{bmatrix} \dot{\theta}_1\left(c_4(-c_4 s_2 d_3 + s_3 s_2 d_3) - s_4(c_2 a_2 - s_{23} d_4 + c_{23} a_3)\right) + \dot{\theta}_2 c_4(s_3 a_2 - d_4) + \dot{\theta}_3 c_4 d_4 \\ \dot{\theta}_1(-s_4(-c_4 s_2 d_3 + s_3 s_2 d_3) - c_4(c_2 a_2 - s_{23} d_4 + c_{23} a_3)) - \dot{\theta}_2 s_4(s_3 a_2 - d_4) - \dot{\theta}_3 s_4 d_4 \\ \dot{\theta}_1(s_3 s_2 d_3 + c_3 s_2 d_3) + \dot{\theta}_2(c_3 a_2 + a_3) + \dot{\theta}_3 a_3 \end{bmatrix} \tag{34} $$

$$ {}^5w_5 = {}^5_4R\ {}^4w_4 + \dot{\theta}_5\ {}^5z_5 = \begin{bmatrix} c_5 & 0 & s_5 \\ -s_5 & 0 & c_5 \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} -s_4\left(\dot{\theta}_2+\dot{\theta}_3\right)-c_4 s_{23}\dot{\theta}_1 \\ -c_4\left(\dot{\theta}_2+\dot{\theta}_3\right)+s_4 s_{23}\dot{\theta}_1 \\ \dot{\theta}_4-\dot{\theta}_1 c_{23} \end{bmatrix} + \dot{\theta}_5 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{35} $$

$$ {}^5w_5 = \begin{bmatrix} c_5\left(-s_4\left(\dot{\theta}_2+\dot{\theta}_3\right)-c_4 s_{23}\dot{\theta}_1\right)+s_5\left(\dot{\theta}_4-\dot{\theta}_1 c_{23}\right) \\ -s_5\left(-s_4\left(\dot{\theta}_2+\dot{\theta}_3\right)-c_4 s_{23}\dot{\theta}_1\right)+c_5\left(\dot{\theta}_4-\dot{\theta}_1 c_{23}\right) \\ c_4\left(\dot{\theta}_2+\dot{\theta}_3\right)-s_4 s_{23}\dot{\theta}_1+\dot{\theta}_5 \end{bmatrix} \tag{36} $$

$$ {}^5\nu_5 = {}^5_4R\left({}^4\nu_4 + {}^4\omega_4 x\, {}^4P_5\right) = \begin{bmatrix} c_5 & 0 & s_5 \\ -s_5 & 0 & c_5 \\ 0 & -1 & 0 \end{bmatrix} \tag{37} $$

$$ \left(\begin{bmatrix} \dot{\theta}_1\left(c_4(-c_4 s_2 d_3 + s_3 s_2 d_3) - s_4(c_2 a_2 - s_{23} d_4 + c_{23} a_3)\right) + \dot{\theta}_2 c_4(s_3 a_2 - d_4) + \dot{\theta}_3 c_4 d_4 \\ \dot{\theta}_1\left((-c_4 s_2 d_3 + s_3 s_2 d_3) - c_4(c_2 a_2 - s_{23} d_4 + c_{23} a_3)\right) - \dot{\theta}_2 s_4(s_3 a_2 - d_4) - \dot{\theta}_3 s_4 d_4 \\ \dot{\theta}_1(s_3 s_2 d_3 + c_3 s_2 d_3) + \dot{\theta}_2(c_3 a_2 + a_3) + \dot{\theta}_3 a_3 \end{bmatrix}\right) \tag{38} $$

$$ {}^5v_5 = \begin{bmatrix} {}^5v_{5x} \\ {}^5v_{5y} \\ {}^5v_{5z} \end{bmatrix} \tag{39} $$

$$ \left.\begin{aligned} {}^5v_{5x} &= \dot{\theta}_1\Bigg(c_5\left(c_4\begin{pmatrix} -c_4 s_2 d_3 \\ +s_3 s_2 d_3 \end{pmatrix} - s_4\begin{pmatrix} c_2 a_2 \\ -s_{23} d_4 \\ +c_{23} a_3 \end{pmatrix}\right) + s_5\begin{pmatrix} s_3 s_2 d_3 \\ +c_3 s_2 d_3 \end{pmatrix} + \dot{\theta}_2\begin{pmatrix} c_5 c_4(s_3 a_2 - d_4) + \\ s_5(c_3 a_2 + a_3) \end{pmatrix} + \dot{\theta}_3(c_5 c_4 d_4 + s_5 a_3) \\ {}^5v_{5y} &= \dot{\theta}_1\left(-s_5\left(c_4\begin{pmatrix} -c_4 s_2 d_3 \\ +s_3 s_2 d_3 \end{pmatrix} - s_4\begin{pmatrix} c_2 a_2 \\ -s_{23} d_4 \\ +c_{23} a_3 \end{pmatrix}\right) + c_5\begin{pmatrix} s_3 s_2 d_3 \\ +c_3 s_2 d_3 \end{pmatrix}\right) + \dot{\theta}_2\begin{pmatrix} c_5\begin{pmatrix} c_3 a_2 \\ +a_3 \end{pmatrix} \\ -s_5 c_4(s_3 a_2 - d_4) \end{pmatrix} + \dot{\theta}_3(c_5 a_3 - s_5 c_4 d_4) \\ {}^5v_{5z} &= \dot{\theta}_1(s_4(-c_4 s_2 d_3 + s_3 s_2 d_3) + c_4(c_2 a_2 - s_{23} d_4 + c_{23} a_3)) + \dot{\theta}_2 s_4(s_3 a_2 - d_4) + \dot{\theta}_3 s_4 d_4 \end{aligned}\right\} \tag{40} $$

The following equation;

$$ {}^{0}_{4}R = {}^{0}_{1}R\,{}^{1}_{2}R\,{}^{2}_{3}R\,{}^{3}_{4}R $$

$$ {}^{0}_{4}\nu = {}^{0}_{4}R\,{}^{4}\nu_{4} \quad (41) $$

finds the velocity with respect to the nonmoving base frame.

4. CONCLUSIONS

In this study, a drilling robot with 5 degrees of freedom was designed and its kinematic analysis was carried out in an effort to provide the infrastructure for the controller design of the robot arm. In the future studies, we are planning to manufacture this robot arm and carry out its computer-aided control. With this robot arm, we aim to ensure that drilling processes especially in the assembly lines are carried out in a computer-controlled way, with less error and within a shorter period of time.

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