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## ANALYSIS OF KINEMATIC FOR LEGS OF A HEXAPOD USING DENAVIT-HARTENBERG CONVENTION

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**Abstract** -- The headway of manipulator robots makes the development of a hexapod quite fast. Unfortunately, a hexapod is unstable to moving in a regular movement with some values added to programming algorithms. Various techniques implemented yet to the algorithms, like entering the degree values of each servo. However, to simplify the implementation of the algorithms, need some equations. This paper offered a hexapod control system based on Arduino that using Denavit-Hartenberg parameters to produce the equations. Various experiments have performed. Based on the experiments the offered system able to simplify the programming algorithms.

**Keywords:** Manipulator robots; Hexapod; Denavit-Hartenberg; Kinematic

Received: March 3, 2018

Revised: April 24, 2018

Accepted: April 24, 2018

### INTRODUCTION

In this century, the significant progress occurred in the field of robotics. Many robots created aiming to emulate, help or make things easier for the human. Robots designed to simplify human tasks or helping to carry out a particular task that cannot be done by a human directly by considerations of time up to security. The robotic system combines design science, mechanics, electronics, and control (Adriansyah and Amin, 2016; Adriansyah et al., 2015; Munadi et al., 2015).

Six-legged robot or commonly called Hexapod is one type of walking robot. Usually, have 12 or 18 servos that serve as the joint of the foot. When compared to a bipedal robot, six-legged robot configuration has great balance while walking, because leaving only 3 feet in the ground and the rest is in the air, will give a great balance (Yang et al., 2014).

However, most of the programmers of these six-legged robots did not use the kinematic equations. They used the old way to codes the program. They make some coding programs that more complicated, lengthy, and a bit difficult to get the servo's angle or the end-effector's distance desired.

Some research has done by some researchers such as (Atique & Ahad, 2014) who designed and created a car robot which powered by a foot-shaped tool with 3 degrees of freedom (DOF). They deduced the kinematics through DH convention and predict the movement of the robotic structure with simulation software then applied to the car robot. With a foot-shaped tool, the car moves at about 0.48 feet/second. The Next, there is (Nookala et al., 2013) which analyzes the

robot leg with 3 DOF who assisted with the simulation through the robotic software called Robo Analyzer and MATLAB. By using Robo Analyzer, they obtained the solution of forwarding and inverse kinematics, then calculated DH parameters theoretically. The computed matrix was matched with the update matrix in Robo Analyzer. And also, MATLAB has obtained forms of a graph which similar to the obtained values in Robo Analyzer. Then there is (Jianhua, 2006) who designed six arm manipulators like legs with 6 DOF each, so the total is 42 DOF for the six-legged robot. The hexapod robot is constructed and could realize the omnidirectional movement. Then the tripod gait of hexapod is simulated.

The purpose of this research is to produce a kinematic algorithm and then be implemented into each leg of the hexapod so that it can control the end effector's distance. This paper use Denavit-Hartenberg convention to solve kinematic equations from one leg afterward implemented to all legs of hexapod and obtained the error values between the input and the reality.

### MATERIAL AND METHOD

#### Material

The hexapod robot (Gao et al., 2015) is consists of one body and six legs. Each leg is consisting of 3 parts, femur, coxa and tibia. The coxa link is enclosed to the body with a joint named base/coxa joint (joint 1), which could rotate around of the body from the axis plumb to the long and wide side. The femur link hooked to the coxa by a joint called hip/femur joint (joint 2) that plumb to both the coxa and joint 1. The tibia link is enclosed to the femur link by a tibia joint (joint 3).

The femur and tibia joints were defined using the most robust servo motor because they will hold the body weight. For the coxa, the joint was determined using servo motor that less strong than femur and tibia joints. Because in this joint, the servo motor is used as swing part, that means move to the right or left without hold the body weight.

The list of components that used in the hexapod has been tested with some lab experiment and simulation to get the suitable components. Such as to hold the body and all its components. A metal aluminum board is chosen for the mechanical structure. The components are listed in Table 1. The components are described in the Fig. 1.

Table 1. List of components

No.	Components	Amount
1	Arduino Mega 2560	1
2	MG995 Servo	12
3	HITEC HS-311 Servo	6
4	Servo Controller	3
5	UBEC 5V 8A	3
6	Battery 3300 mAh	1
7	Bottom Body	1
8	Top Body	1
9	Layer	1
10	Coxa, Femur, Tibia Bracket	6

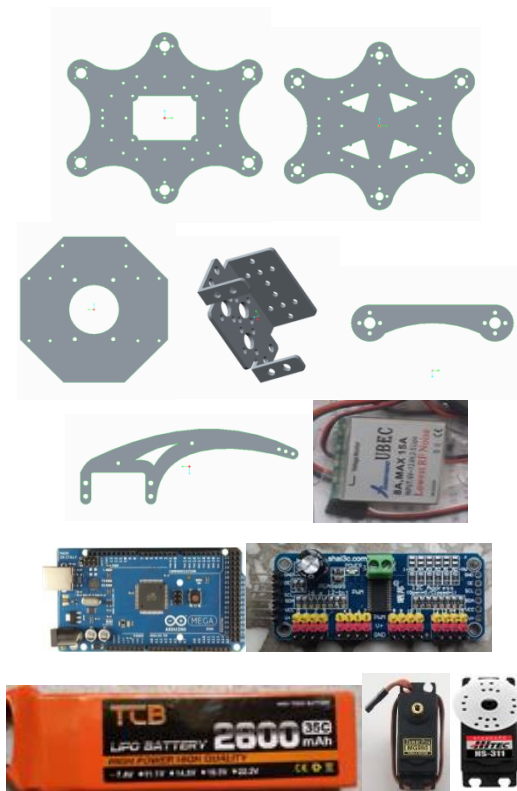


Figure 1. Components of Hexapod

## Arduino

Arduino (Supegina & Iklima, 2015) is an open source of single-board micro-controller and could be used in various fields of electronics. It used as the main part that controls all of the components, processes the logic programming to generate the output then sends it to the servos. An Arduino Mega 2560 is chosen based on the total number of its digital input/output pins.

## Servo

The hexapod requires several servos on its leg construction. To actuate a robot some motors are needed. There are two types of a servo motor, Tower Pro MG995, and HITEC HS-311. Each servo motor has different stall current. For Tower Pro MG995 is 1.5 Ampere (A) each and HITEC HS-311 is 700 mA each. In one leg used 2 Tower Pro MG995 and 1 HITEC HS-311. So, in 1 leg will need current supply at least 3.7 A. And all the legs will need current consumption around 22.2 A. In that case, it used 3 UBEC 8A (total 24 A) to avoid damaging the servo motors.

## Servo Controller

The Arduino Mega board, PWM output is 15 pins and for hexapod robot needs an external servo drive, because it needs 18 pins for a servo, so that is not sufficient to move in. Through this servo driver, it can drive 16 servos individually over I2C with only two pins. It allows using the SDA and SCL pins on the Arduino.

## UBEC

Universal Battery Elimination Circuit (UBEC) is an electronic circuit which spigot the power of the battery and decreases the voltage to 5 or 6 volts (V).

## Mechanic Design

The hexapod robot is contained a bottom body, top body, a layer, six coxa brackets, six femur links and six tibia links. This upper body part in Fig. 1 has a rectangular shape with 175 mm length and 155 mm width, six joint points for the legs and a rectangle hole in the middle that used for the cable of the components line. The bottom body has the same shape as the upper body, rectangular shape with 175 mm length and 155 mm width, six joint points for the legs. This additional layer part has hexagon shape with 55 mm length of each side and a hole in the middle with radius 22.5 mm lengths. It was made with like acrylic component with the red color.

Coxa bracket is a place for servo one and two holders. Femur link is a connector for joint 2 (femur joint) with joint 3 (tibia joint) with 110 mm total length. Tibia link is a connector for joint 3

(tibia joint) with the end-effector, with 16.45 mm entire length from top to bottom.

In the Fig. 2 the offset length is 3.2 cm from the bottom body to the femur joint. The length from the center joint of coxa to the center joint of a

femur is 3 cm. And the length from the center joint of a femur to the center joint of the tibia is 8.5 cm and from the center joint of the tibia to the end-effector is 12.5 cm.

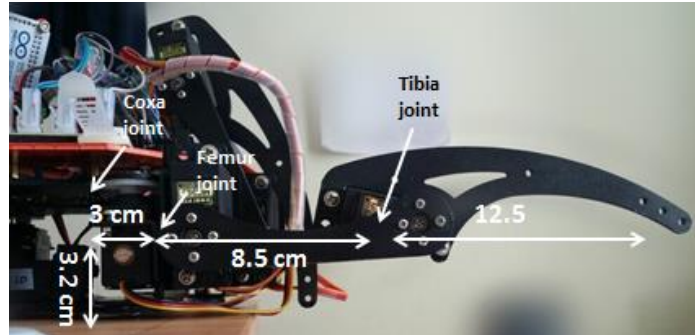


Figure 2. The Structure leg of Hexapod

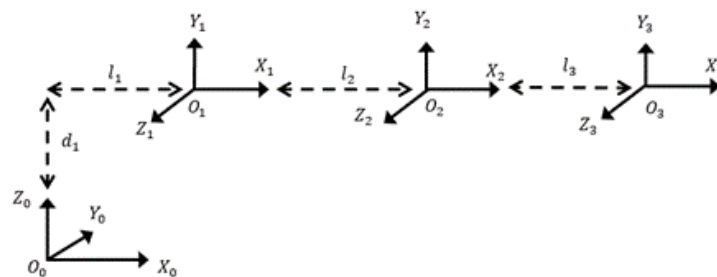


Figure 3. Frame Coordinate

## Method

The electronic hardware system is tested in a virtual environment (simulation) to avoid the damage. In the same way, the robotic structure plays an important role to get the mathematical equation modeling. It well presents the design summary of the robot dynamics in parametric equations form. It assists to choose feasibility, set up and settle the design. Theory of forwarding and inverse kinematics provided the way out a model of the proposed hexapod. (Akhlaq et al., 2014)

Kinematics in robotics (Beni, 2011) is a representation shape regarding the geometrical explanation of a robot structure. From the geometrical equation, it could get the connection between joints spatial geometry concept and end-effector coordinates theory to figure an object position. The purpose of kinematics is to determine the relative position of a frame to its original coordinates.

Forward kinematics is transforming the joint variable to the end-effector position. Besides that, inverse kinematics is to transform the end-effector position to the joint variable.

The Denavit-Hartenberg parameters (also called DH parameters) (Melek, 2010) are the four parameters related with a particular convention for

enclosing the reference frames to the links of a spatial, kinematic chain or robot manipulator.

- Joint offset ( $d$ ): length of junctions of ordinary on the joint axis.
- Joint angle ( $\theta$ ): angle between the orthogonal projections of the common normal to the plane normal to the joint axes.
- Link length ( $a$ ): the range among the common normal to the axis.
- Twist angle ( $\alpha$ ): the angle between the orthogonal projections of the joint axes onto a plane normal to the common normal.  $\theta$  is variable if a joint is revolute,  $\alpha$  is variable if a joint is prismatic.

For this hexapod, the frame coordinates are represented in the Fig. 3.

After determining the coordinates of each frame ( $x$ ,  $y$ , and  $z$ ), the Denavit-Hartenberg (DH) parameters of the link could be determined as shown in Table 2.

Table 2. Denavit-Hartenberg parameters

Link	DH Parameters			
$i$	$\alpha_i$	$a_i$	$d_i$	$\theta_i$
1	90	$l_1$	$d_1$	$\theta_1$
2	0	$l_2$	0	$\theta_2$
3	0	$l_3$	0	$\theta_3$

Forward Kinematics (Akhlag et al., 2014) describes the relationship of each joint of the robotic legs and in supplementary to that, it also as frames for the positioning and alignment of end-effector. With the provided values of joint variables could unpack the coordinates.

Homogenous transformation matrix of the hexapod could be defined using the Denavit-Hartenberg (DH) Convention. The calculation is as follow:

This is a translation by  $d_1$  (offset link) and translation by  $l_1$  (link length) followed by a rotation around  $X_1$  and  $Z_1$  axis (twist angle).

$${}^0_1T = \begin{bmatrix} \cos \theta_1 & 0 & \sin \theta_1 & l_1 \cos \theta_1 \\ \sin \theta_1 & 0 & -\cos \theta_1 & l_1 \sin \theta_1 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

This is a translation by  $l_2$  (link length) followed by a rotation around  $Z_2$  axis (joint angle).

$${}^1_2T = \begin{bmatrix} \cos \theta_2 & -\sin \theta_2 & 0 & l_2 \cos \theta_2 \\ \sin \theta_2 & \cos \theta_2 & 0 & l_2 \sin \theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

This is a translation by  $l_3$  (link length) followed by a rotation around  $Z_3$  axis (joint angle).

$${}^2_3T = \begin{bmatrix} \cos \theta_3 & -\sin \theta_3 & 0 & l_3 \cos \theta_3 \\ \sin \theta_3 & \cos \theta_3 & 0 & l_3 \sin \theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

Transformation of link 0 to link 3 is the result of the transformation matrix of each link

$${}^0_3T = {}^0_1T {}^1_2T {}^2_3T \quad ((4))$$

From this calculation we get:

$$p_x = x = c\theta_1(c(\theta_2 + \theta_3)l_3 + c\theta_2l_2 + l_1) \quad (5)$$

$$p_y = y = s\theta_1(c(\theta_2 + \theta_3)l_3 + c\theta_2l_2 + l_1) \quad (6)$$

$$p_z = z = s(\theta_2 + \theta_3)l_3 + s\theta_2l_2 + d_1 \quad (7)$$

Inverse kinematics are solutions to obtain the joint angle values needed to achieve the desired position using algebraic approach. Algebraic approach is to perform a decrease kinematics equation described by the matrix transformation.

From Forward Kinematic Equ. (4)((4), if it multiplies both sides with  $[{}^0_1T]^{-1}$

Where,

$$[{}^0_1T]^{-1} = \begin{bmatrix} c\theta_1 & s\theta_1 & 0 & -l_1 \\ 0 & 0 & 1 & -d_1 \\ s\theta_1 & -c\theta_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ((8))$$

It can obtain, that:

$${}^0_3T [{}^0_1T]^{-1} = [{}^0_1T]^{-1} {}^0_1T {}^1_2T {}^2_3T \quad ((9))$$

$${}^0_3T [{}^0_1T]^{-1} = {}^1_2T {}^2_3T \quad (10)$$

$$\begin{bmatrix} \dots & \dots & \dots & p_x c\theta_1 + p_y s\theta_1 - l_1 \\ \dots & \dots & \dots & p_z - d_1 \\ \dots & \dots & \dots & p_x s\theta_1 - p_y c\theta_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \dots & \dots & \dots & c(\theta_2 + \theta_3)l_3 + c\theta_2l_2 \\ \dots & \dots & \dots & s(\theta_2 + \theta_3)l_3 + s\theta_2l_2 \\ \dots & \dots & \dots & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

From this calculation it gets:

$$\theta_1 = \text{Atan2}(p_y, p_x) \quad (12)$$

All the thetas could be described explicitly in Fig. 4, in this case, because this manipulator is a leg of the hexapod, so the value of  $\theta_3$  could be negative due to reach value  $z < 0$  of the end-effector.

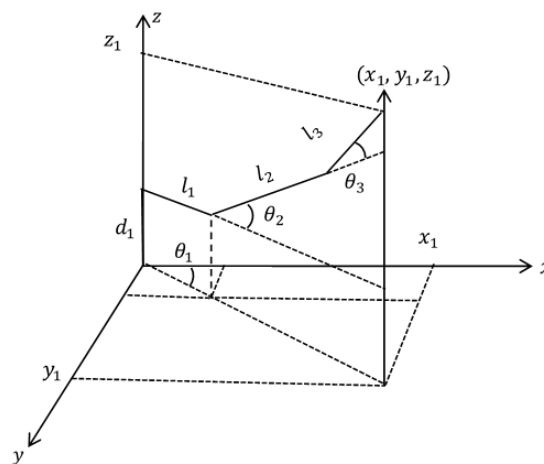


Figure 4. Leg Manipulator

In his book (Jakimovski, 2011), because it has six legs, compose from more than one servo joints, they described hexapod robots belong to the group of walking robots. Distributed in two different groups located on the two opposite sides of the robot's body, the legs of the robot are usually symmetrically. The scheme design of hexapod robots is often inspired by locomotion systems of insects such as cockroaches or insects.

One servo per joint could manipulate the joints, providing 3 DOF (degrees of freedom) for each leg, total 18 DOF. One servo (coxa/hips) connects entire leg to the chassis through a vertical axis, allowing the leg to rotate sideways concerning the body. The two other servos (femur and tibia) manipulate the other joints of the leg with rotation about horizontal axes. The schematic diagram for the hexapod is as shown in Fig. 5.

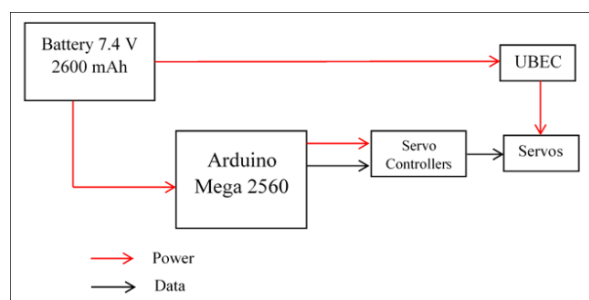


Figure 5. Schematic Diagram of the Hexapod

The function each part of the diagram is as follows. Battery 7.4V/2600 mAh is used as power supply for 3 UBECs 5V/8A and Arduino. Arduino Mega 2560 is used as a control system for the Hexapod robot. UBEC 5V/8A is used to regulate the voltage down to the necessary 5 or 6 volts for the servos with 8A current each UBEC. Servo motors are used as joint to connect between links in the legs.

Servo controllers with PWM used to control the position of the servos.

## RESULTS AND DISCUSSION

In this section, is implementing the inverse kinematic into each leg of hexapod and obtained the angle values of each joint. The angle values were automatically set into the program. We only need to put the values of x, y, and z coordinate. We tried one by one of each position and get the value of error. The error is the difference value between desired and test value. We simulated these to all the legs. First, we need to assemble the mechanic design and components in Fig. 6.



Figure 6. Hexapod Robot

Based on Fig. 2, it gets the DH parameters that shown in Table 3.

Table 3. Denavit-Hartenberg Parameter of The Hexapod

Link	DH Parameters			
i	$\alpha_i$	$a_i$	$d_i$	$\theta_i$
1	90	3	3.2	$\theta_1$
2	0	8.5	0	$\theta_2$
3	0	12.5	0	$\theta_3$

For the test, it chooses 7 points each position (x, y, z coordinates) for one leg, all is in centimeter and the results are listed in Table 4 to Table 9.

Table 4. Test for Leg 1

Post		Values (cm)							
Leg 1	X	Desire	7	8	9	10	11	12	13
		Test	7.2	8.1	9.2	10	11	11.8	12.8
		Error	0.2	0.1	0.2	0	0	0.2	0.2
	Y	Desire	1	2	3	4	5	6	7
		Test	1.3	2.1	3	4	5	5.8	6.7
		Error	0.3	0.1	0	0	0	0.2	0.3
	Z	Desire	-5	-4	-3	-2	-1	1	2
		Test	-5.1	-4	-2.9	-1.9	-0.9	0.8	1.9
		Error	0.1	0	0.1	0.1	0.1	0.2	0.1

Table 5. Test for Leg 2

Post		Values (cm)							
Leg 2	X	Desire	7	8	9	10	11	12	13
		Test	6.8	8	8.8	9.9	10.7	11.8	12.8
		Error	0.2	0	0.2	0.1	0.3	0.2	0.2
	Y	Desire	-3	-2	-1	1	2	3	4
		Test	-3	-1.9	-0.9	1.1	2.2	3.1	4.1
		Error	0	0.1	0.1	0.1	0.2	0.1	0.1
	Z	Desire	-5	-4	-3	-2	-1	1	2
		Test	-5.1	-4.1	-3.1	-2	1	1.1	1.9
		Error	0.1	0.1	0.1	0	0	0.1	0.1

Table 6. Test for Leg 3

Post		Values (cm)							
Leg 3	X	Desire	7	8	9	10	11	12	13
		Test	6.8	7.8	9.8	10.8	11.7	12.8	13.8
		Error	0.2	0.2	0.2	0.2	0.3	0.2	0.2
	Y	Desire	1	2	3	4	5	6	7
		Test	0.9	1.9	2.9	4	4.9	5.9	6.9
		Error	0.1	0.1	0.1	0	0.1	0.1	0.1
	Z	Desire	-5	-4	-3	-2	-1	1	2
		Test	-5.2	-4.2	-3	-2	-1	1.2	2
		Error	0.2	0.2	0	0	0	0.1	0

Table 7. Test for Leg 4

Post		Values (cm)							
Leg 4	X	Desire	7	8	9	10	11	12	13
		Test	6.8	7.8	8.8	9.9	10.7	11.8	12.8
		Error	0.2	0.2	0.2	0.1	0.3	0.2	0.2
	Y	Desire	1	2	3	4	5	6	7
		Test	0.8	1.8	2.8	3.7	4.7	5.7	6.8
		Error	0.2	0.2	0.2	0.3	0.3	0.3	0.2
	Z	Desire	-5	-4	-3	-2	-1	1	2
		Test	-5.1	-4.1	-3	-1.9	-0.9	1.2	2.2
		Error	0.1	0.1	0.3	0.1	0.1	0.2	0.2

Table 8. Test for Leg 5

Post		Values (cm)							
Leg 5	X	Desire	7	8	9	10	11	12	13
		Test	6.8	7.9	8.8	10	11	11.9	12.9
		Error	0.2	0.1	0.2	0	0	0.1	0.1
	Y	Desire	-3	-2	-1	1	2	3	4
		Test	-2.9	-1.9	-0.9	1	2	2.8	3.9
		Error	0.1	0.1	0.1	0	0	0.2	0.1
	Z	Desire	-5	-4	-3	-2	-1	1	2
		Test	-4.8	-3.9	-3.1	1.9	-0.9	1	1.9
		Error	0.2	0.1	0.1	0.1	0.1	0	0.1

Table 9. Test for Leg 6

Post		Values (cm)							
Leg 6	X	Desire	7	8	9	10	11	12	13
		Test	7.2	8.2	9.3	10.3	11.3	12.4	13.4
		Error	0.2	0.2	0.3	0.3	0.3	0.4	0.4
	Y	Desire	1	2	3	4	5	6	7
		Test	1	2.1	3.1	4.1	5.1	6.2	7.2
		Error	0	0.1	0.1	0.1	0.1	0.2	0.2
	Z	Desire	-5	-4	-3	-2	-1	1	2
		Test	-5.2	-4.2	-3.2	-2.1	-0.9	1.1	2.1
		Error	0.2	0.2	0.2	0.1	0.1	0.1	0.1

From Leg 1 (in Table 4) the error values lie from 0.1 to 0.2 cm. From Leg 2 (Table 5) the error values lie from 0.1 to 0.3 cm. From Leg 3 (Table 6) the error values lie from 0.1 – 0.3 cm. From Leg 4 (Table 7) the error values lie from 0.1 – 0.3 cm. From Leg 5 (Table 8) the error values lie from 0.1 – 0.2 cm. From Leg 6 (Table 9) the error values lie from 0.1 – 0.4 cm.

## CONCLUSION

The hexapod robot was constructed and kinematic equations with DH parameters were obtained. The results of implementation inverse kinematic to each leg are shown in the result. In the leg 1, 2, 3 and 4 the range of error value is from 0.1 – 0.3 cm, leg 5 is from 0.1 – 0.2 cm and leg 6 is from 0.1 – 0.4 cm. The accuracy of this method is more than 90% where the error value lies on 0.1 to 0.4 cm. This means that the inverse kinematics of the legs is correct. This range of error caused by some human error, such as in the assembly part is not equilibrium from one link to another, and also the measurement of constraint value of each servo is not accuracy from 0 degrees to 180 degrees.

## ACKNOWLEDGMENT

We thank our colleagues from Beijing Institute of Technology and Universitas Mercu Buana who provided insight and expertise that greatly assisted the research.

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