Improvement of DC Motor Speed Control for Mobile Robot to Minimize Slip Phenomenon

Bayu Sandi Marta[1], Dewi Mutiara Sari[2]

[1] *Politeknik Elektronika Negeri Surabaya*

[bayu, dewi.mutiara]@pens.ac.id

Abstract— Slip on the mobile robot has a significant impact on the maneuver and the accuracy of the mobile robot movement. The slip phenomenon occurs because of the loss of traction between the surface and the wheels due to the spontaneous acceleration or declaration application. This paper presents a method to improve DC motor performance by using slip control as an observer such that the slip phenomenon effect can be minimized. The performance that will be analyzed is the accuracy of motor speed and robot position accuracy when the robot is moving. The result shows that the Root Mean Squared Error (RMSE) for the motor speed performance that does not use slip control is 2.680, the system using slip control produces RMSE 1.3393. Regarding the robot position accuracy, the RMSE of the system that does not use slip control is 0.0379, the system using slip control is 0.0065.

Keywords— Slip, Omnidirectional, Mobile Robot, DC Motor Speed.

I. Introduction

Mobile robots are one type of robot that can be implemented in many fields, starting from industry, defense and security, transportation, and others. As explained by Pandey et al., the research on mobile robots is still developing today in [1]. There are various problems found in the issue of mobile robots. One of them is maneuverability. Issues in the mobile robot maneuvering experiment. The resulting precision reaches an error of approximately 15 degrees using a speed of 8 m/s [2].

The mobile robot with Omni-directional drive has the advantage of maneuvering because of the wheels' unique structure. There are rollers around it with a certain angle to the direction of the wheels. Mobile robots can maneuver in various directions in the planar plane, as stated Long [3]. This capability is since the mobile robot is equipped with wheels with a roller around it with a certain angle to the direction of rotation of the wheels. For a standard Omni wheel, the angle is perpendicular to the wheel rotation, and for a mecanum wheel, the angle is 45^o from the direction of the wheel rotation. This allows the wheels to rotate according to the actuator's rotation and also to rotate laterally. Generally, a mobile robot is used more than 3 Omni wheels to become an omnidirectional robot.

The Omni wheel on a mobile robot with an Omni-directional drive, which is implemented in fast movement [4]. The Omni wheel has simple control and steering but has limited traction. This affects the slip phenomenon [5] detected slip using redundant encoders on an omnidirectional wheeled mobile robot. The largest slip occurred at the Omni wheel (three wheels), which reached 0.3 m/s. Also, slip occurs when the robot accelerates or decelerates spontaneously or at a high rate. If this slip occurs continuously, it will cause the control to be inaccurate so that the mobile robot's motion precision level will decrease.

To minimize the occurrence of slippage on the mobile robot, it is necessary to apply settings during acceleration and deceleration so that it does not occur spontaneously at high rates. This acceleration setting should not be too low or too long because it will cause the maneuvering of the mobile robot to be less than optimal. A achieve maximum results. These accelerations and decelerations must be carried out as quickly as possible but do not cause traction between the wheels and the floor surface to be lost to avoid slippage. DC motors are also implemented in many different case studies, including for data processing in automatic sliding doors [6] and for adjusting the speed and direction of rotation of the umbrella drive [7].

In this study, a mobile robot actuator control system will be built, in this case, a DC motor to reduce slippage occurrence. Acceleration settings will be applied to each actuator based on parameters that affect the actuator's strength and torque. This research aims to build a control system to reduce the slip problem on the mobile robot driving wheel to increase the precision and efficiency in its movement.

II. Research Methodology

This section discussed four sub-sections regarding omnidirectional kinematics, control of dc motor, slip control, and mobile robot movement control.

A. Omnidirectional Kinematic

Mobile robot kinematics is the study of motion in mobile robots regardless of the supporting factors. Kinematics only discusses how the robot moves or changing positions in a field of work. The kinematics of mobile robots depend on the type of locomotion. This is because the type of drive affects the ability of the robot to change positions. For the mobile robot with the omnidirectional wheels, the configuration is depicted in Figure 1.

Taheri H., *et al,* explained in [12] regarding the kinematics of Omni wheel configuration which is depicted in Figure 1. i is the index of wheels. v_x and v_y are robot linear velocities with the [*m/s*] unit. ω_z is robot angular velocity with the [*rad/s*] unit. v_{ir} is the velocity of the passive roller in the wheel i. $v_{i\omega}$ [*m/s*] is the velocity vector concerning the wheel revolutions, (i =

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0,1,2,3) ϵ *R*. S_i and E_i are the coordinate system of *i* th wheel. P_i is the wheel's center point. α_i is the angle between OP_i and X_R.

Meanwhile, X_R, O, Y_R are the mobile robot's base frame, the Cartesian coordinate. θ is the orientation angle. l_{ix} is half of the distance between front wheels, and l_{iy} is half of the distance between the front wheel and rear wheel.

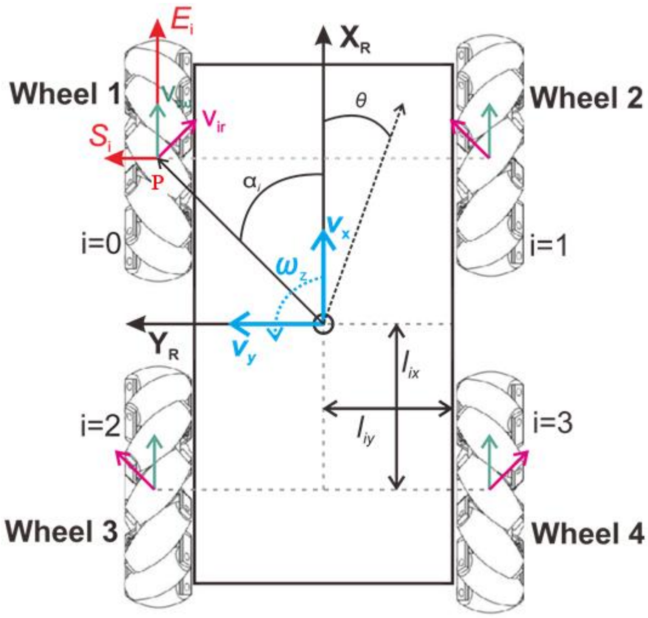

Figure 1. Mechanical design of omnidirectional wheels

The configuration of the wheel is illustrated in Figure 2. Based on Figure 2 and Figure 1, the wheel velocity (center point) concerning the frame X_ROY_R is described in Equation (1)(2).

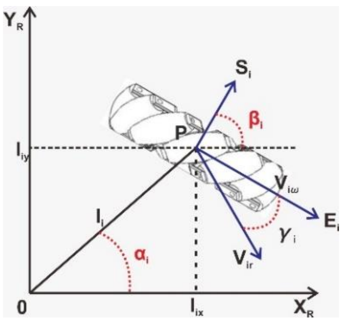

Figure 2. Wheel configuration in the robot frame

$$\begin{bmatrix} V_{iX_R} \\ V_{iY_R} \end{bmatrix} = \begin{bmatrix} \cos\beta_i & -\sin\beta_i \\ \sin\beta_i & \cos\beta_i \end{bmatrix} \begin{bmatrix} v_{S_i} \\ v_{E_i} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_{iX_R} \\ V_{iY_R} \end{bmatrix} = {}^{w_i}T_{P_i}\,{}^{p_i}T_R \begin{bmatrix} \omega_i \\ v_{i_r} \end{bmatrix} \quad (2)$$

With ${}^{p_i}T_R$ is the transformation matrix calculated from the *i*-th center of the wheels concerning the robot coordinate system. Because the motion of the robot is planar, then it is explained in Equation (3)(4)(5),

$$\begin{bmatrix} V_{iX_R} \\ V_{iY_R} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -l_{i_y} \\ 0 & 1 & l_{i_x} \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} V_{iX_R} \\ V_{iY_R} \end{bmatrix} = T' \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} V_{iX_R} \\ V_{iY_R} \end{bmatrix} = T' \begin{bmatrix} v_{X_R} \\ v_{Y_R} \\ \omega_R \end{bmatrix} \quad (5)$$

Meanwhile for ${}^{w_i}T_{P_i}$ is regarding the wheel motion principle of *i*-th wheel. The configuration of wheel motion is described below,

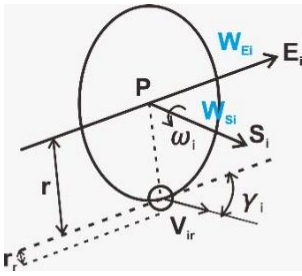

Figure 3. The *i*-th wheel configuration

The v_{ir} is the velocity of *i*-th wheel for the S_i P_i E_i frame. Meanwhile, w_{Ei} is the free roller tangential velocity that is touching to the floor. The equations are described in Equation (6)(7), with *i* = 0, 1,2, 3,

$$v_{i_r} = \frac{1}{\cos 45} r_r \omega_i \quad (6)$$

$$w_{Ei} = r_r \omega_i \quad (7)$$

Based on Figure 3, the v_{Si} and v_{Ei} (velocity of *i*-th wheel) in S_i P_i E_i frame can be depicted as transformation matrix in Equation (8)(9)(10),

$$\begin{bmatrix} V_{S_i} \\ V_{E_i} \end{bmatrix} = \begin{bmatrix} 0 & \sin\gamma_i \\ r_i & \cos\gamma_i \end{bmatrix} \begin{bmatrix} \omega_i \\ v_{i_r} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} V_{S_i} \\ V_{E_i} \end{bmatrix} = {}^{w_i}T_{P_i} \begin{bmatrix} \omega_i \\ v_{i_r} \end{bmatrix}$$

With,

$$v_{Ei} = \omega_i r_i + v_{ir} \cos\gamma_i \quad (9)$$

$$v_{S_i} = v_{ir} \sin\gamma_i \quad (10)$$

Then for the inverse kinematic formulation of the robot, based on Equation (2)(3), it can be obtained in Equation (11),

$$\begin{bmatrix} \omega_i \\ v_{i_r} \end{bmatrix} = {}^{w_i}T_{P_i}{}^{-1} . {}^{p_i}T_R{}^{-1} . T' \begin{bmatrix} v_{X_R} \\ v_{Y_R} \\ \omega_R \end{bmatrix} \quad (11)$$

With the determinant ${}^{wi}T_{Pi}$ and ${}^{Pi}T_R$ are not equal to zero. After that, to obtain the linear velocity (v_{ir}) and the rotational

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velocity (ω_i) of i-th wheel, it can be derived in Equation (12)(13)(14),

$$\begin{bmatrix} v_{X_R} \\ v_{Y_R} \\ \omega_R \end{bmatrix} = T^{+} \begin{bmatrix} \omega_i \\ v_{i_r} \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} \omega_i \\ v_{i_r} \end{bmatrix} = T \begin{bmatrix} v_{X_R} \\ v_{Y_R} \\ \omega_R \end{bmatrix} \tag{13}$$

$$\begin{bmatrix} \omega_i \\ v_{i_r} \end{bmatrix} = \begin{bmatrix} \cos\beta_i & -\sin\beta_i \\ \sin\beta_i & \cos\beta_i \end{bmatrix}^{-1} \begin{bmatrix} 0 & \sin\gamma_i \\ r_i & \cos\gamma_i \end{bmatrix}^{-1} \begin{bmatrix} 1 & 0 & -l_{i_y} \\ 0 & 1 & l_{i_x} \end{bmatrix} \begin{bmatrix} v_{X_R} \\ v_{Y_R} \\ \omega_R \end{bmatrix} \tag{14}$$

With $l_{iy} = l_i \sin \alpha_i$, and $l_{ix} = l_i \cos \alpha_i$ and considering that all the wheels size are the same. Then obtained the transformation matrix as stated in Equation (15),

$$T = \frac{1}{-r} \begin{bmatrix} \frac{\cos(\beta_i-\gamma_i)}{\sin(\gamma_i)} & \frac{\sin(\beta_i-\gamma_i)}{\sin(\gamma_i)} & \frac{l_i \sin(-\alpha_i+\beta_i-\gamma_i)}{\sin(\gamma_i)} \\ -\frac{r\cos(\beta_i)}{\sin(\gamma_i)} & -\frac{r\sin(\beta_i)}{\sin(\gamma_i)} & -\frac{l_i \sin(-\alpha_i+\beta_i) r}{\sin(\gamma_i)} \end{bmatrix} \tag{15}$$

Recall that there is a relation between the angular and linear velocity for each joint (ω_i and v_{ir}). Then the inverse kinematic is formulated as in Equation (16)(17),

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} = \frac{1}{-r} \begin{bmatrix} \frac{\cos(\beta_i-\gamma_i)}{\sin(\gamma_i)} & \frac{\sin(\beta_1-\gamma_1)}{\sin(\gamma_1)} & \frac{l_i \sin(-\alpha_i+\beta_i-\gamma_i)}{\sin(\gamma_i)} \\ \frac{\cos(\beta_2-\gamma_2)}{\sin(\gamma_2)} & \frac{\sin(\beta_2-\gamma_2)}{\sin(\gamma_2)} & \frac{l_2 \sin(-\alpha_2+\beta_2-\gamma_2)}{\sin(\gamma_2)} \\ \frac{\cos(\beta_3-\gamma_3)}{\sin(\gamma_3)} & \frac{\sin(\beta_3-\gamma_3)}{\sin(\gamma_3)} & \frac{l_3 \sin(-\alpha_3+\beta_3-\gamma_3)}{\sin(\gamma_3)} \\ \frac{\cos(\beta_4-\gamma_4)}{\sin(\gamma_4)} & \frac{\sin(\beta_4-\gamma_4)}{\sin(\gamma_4)} & \frac{l_4 \sin(-\alpha_4+\beta_4-\gamma_4)}{\sin(\gamma_4)} \end{bmatrix} \begin{bmatrix} v_X \\ v_Y \\ \omega_Z \end{bmatrix} \tag{16}$$

$$\begin{bmatrix} v_X \\ v_Y \\ \omega_Z \end{bmatrix} = T^{+} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} \tag{17}$$

B. DC Motor Control

DC motors are commonly used as wheel drives in mobile robots. Some of the advantages of using a DC motor besides the low cost are the relatively simpler rotational speed settings compared to the other types of motors. Many methods can be used to adjust the rotational speed of a DC motor, including using PI control or PID control, fuzzy control, and the other types of control as conducted by Ang, *et al*, in [11] and Tzou, *et al*, in [8].

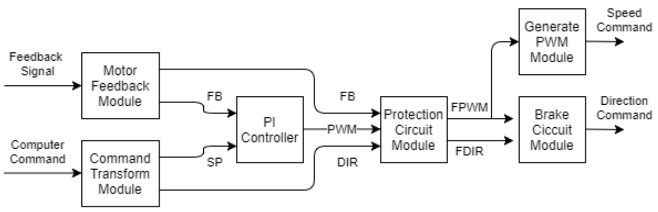

Figure 4. The architecture of the DC Motor velocity controller

Shih-an Li, *et al*, in [11] designed a DC motor control system for mobile robots using their FPGA chip processor. The control used is the PI controller equipped with a protection circuit module to avoid damage to the motor driver IC due to the large back-EMF that appears, mainly when the motor rotates in the opposite direction repeatedly. The architecture of the motor control is illustrated in Figure 4.

C. Slip Control

In this research, a mobile robot with a mecanum wheel configuration will be used as the test object. The actuator control system will be built to reduce the slip on the drive wheels when the robot maneuvers. The actuator used is a Geared DC motor connected to the mecanum wheel. Each actuator has a rotary encoder sensor and a current sensor. The configuration of the mobile robot is shown in Figure 5.

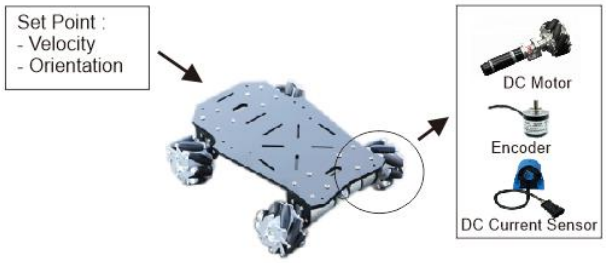

Figure 5. The mobile robot configuration

Motion control of the mobile robot used kinematics motion. The input parameters of the motion are velocity and orientation. The kinematic Equation's output is the number of motion vectors on each actuator (in this case is a DC motor).

The DC motor rotation is regulated using the Pulse Width Modulation (PWM) technique to allow the DC motor to produce rotations with varying speeds. Slip-on the drive wheel will occur when the wheel loses traction or its maximum friction. This can be caused by too high or spontaneous acceleration or deceleration. In the case of the omnidirectional wheel, especially the mecanum wheel, the possibility of slippage is very high because the touchpoint of the wheel to the floor surface is very small, and the touchpoint is on a roller with a 45° inclination of the wheel plane.

So to reduce the slippage, the slip estimation is applied to the system. Figure 6 describes the control of motor DC using slip estimation based on the observer. Using the set point of angular velocity (RPM) will be processed using PID control to produce signal control. PID control is used to adjust the DC motor's speed in real-time to match a given set point. The output of PID control (signal control) will be processed into the driver motor based on current.

Then the output (current) equipped with the slip estimation is calculated. Besides the current from the drive motor output, the current estimate from the observer is calculated. The current estimation is becoming feedback in this system. The input is the result of slip estimation based on the observer. The output of the system is RPM that has been added to the slip

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control estimation. The process will be looped until it is following the specified RPM set of points.

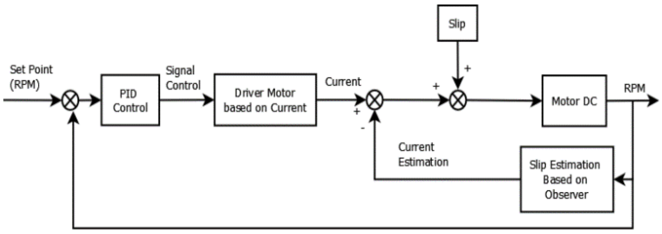

Figure 6. The control of motor equipped with slip estimation

III. Result and Discussion

The results consist of three parts. The experiment regarding DC motor speed using PID controller, current sensor, the system without using slip control, and the system using slip control.

A. DC Motor Speed using PID Controller

This experiment is carried out by running a DC motor following the RPM setpoint value given. Observe the motor's response, whether the motor speed can equal or near the given RPM setpoint, and maintain motor rotation if there is a disturbance (briefly held).

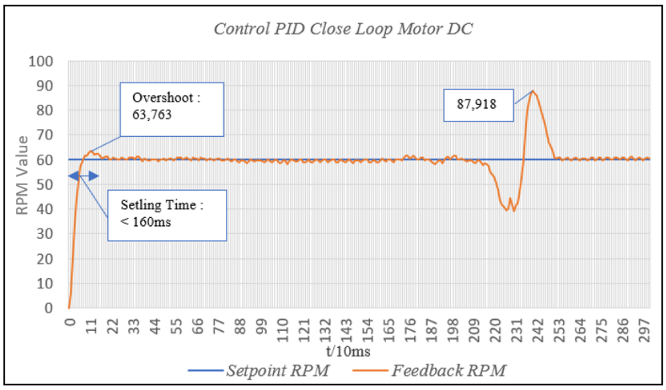

Figure 7. The PID response graphic for RPM 60

By using combination values between RPM speed and PID value (Kp, Ki, and Kd). When RPM speed of 60 and configuration parameters PID Kp = 4.05, Ki = 210, and Kd = 0.0004, the response is depicted in Figure 7. A graph produced by the motor's movement when the setpoint speed is 60 RPM. Settling time on DC motor RPM feedback takes less than 160 milliseconds. Then the overshoot that occurred was up to 63.763 RPM. When the motor is disturbed by being held for a moment, the PID control system will respond to maintain the speed setpoint that has been given to the control system, even though it takes around 250 milliseconds. There is a value of RPM achieved 87.918 RPM.

The RPM value is set to be 180. the result is shown in Figure 8. Based on Figure 8, the settling time on DC motor RPM feedback takes less than 120 milliseconds. Then the overshoot that occurred was up to 187.347 RPM. When the motor is disturbed by being held for a moment, the PID control system will respond to maintain the speed setpoint that has been given to the control system, even though it takes around 250 milliseconds. There is a value of RPM achieved 322.351 RPM.

The next RPM given is 360. The response is illustrated in Figure 9. Figure 9 takes less than 320 milliseconds for the system to achieve the settling time. Then for the overshoot, the system reaches 379.347 RPM. Meanwhile, when the motor is being held for a while (as the disturbance), the PID control system needs around 76 milliseconds to stick to the setpoint value. Although in the process, it also happens the RPM value about 379.347.

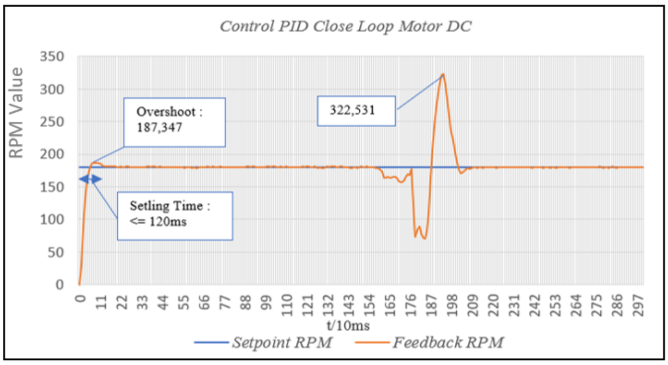

Figure 8. The PID response graphic for RPM 180

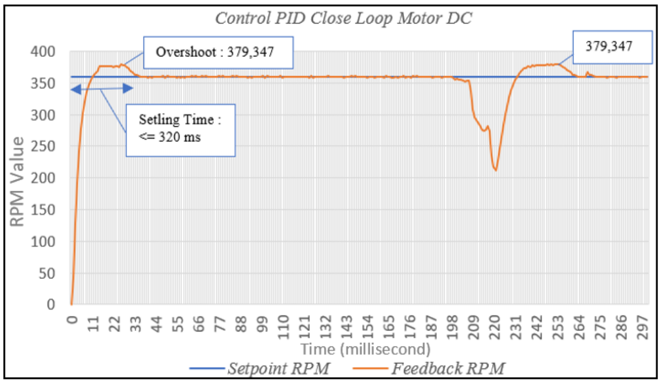

Figure 9. The PID response graphic for RPM 360

B. System without Slip Control

The system testing is carried out without using a slip control, which causes the slip phenomenon effect. Some of the things that are analysed by the occurrence of slip are the motor speed response as seen from the RPM value, the effect of the slip on the wheel distance, the odometry of the robot's movement, and the orientation of the robot.

Firstly, the motor speed response is analysed using the RPM value that is illustrated in Figure 10. In the Omni mechanism, there are four motors. Figure 10 is a graph that shows the motor speed response when the robot is moving. As shown in Figure 11, there is one motor that slips. It affects the RPM, which suddenly rises and then falls back to the initial RPM. The deviation of the RPM value occurs during 0.25 seconds. Figure 10 is tested with 1303 data from 0 up to 3 seconds. Then it is presented with 20 sample data in Table I.

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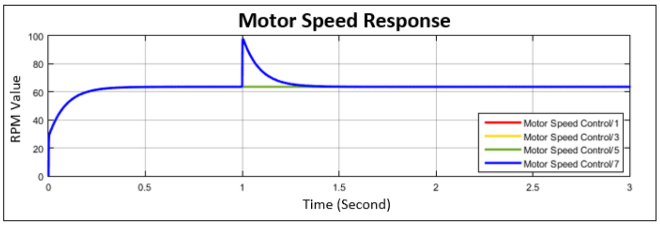

Figure 10. Motor speed response graphic

TABLE I
SAMPLE OF MOTOR SPEED RESPONSE DATA

Time (Second)	Motor 1 (RPM)	Motor 2 (RPM)	Motor 3 (RPM)	Motor 4 (RPM)
3.155E-30	1.2748E-25	1.2748E-25	1.2748E-25	1.2748E-25
0.125035	55.121477	55.121477	55.121477	55.121477
0.277876	62.154554	62.154554	62.154554	62.154554
0.4303563	63.393123	63.393123	63.393123	63.393123
0.5829469	63.610256	63.610256	63.610256	63.610256
0.735910	63.643545	63.643545	63.643545	63.643545
0.8889701	63.642603	63.642603	63.642603	63.642603
1.0131593	63.661718	63.661718	63.661718	94.727632
1.1654113	63.661960	63.661960	63.661960	69.048447
1.3161291	63.662038	63.662038	63.662038	64.544272
1.4689969	63.662064	63.662064	63.662064	63.731436
1.6214590	63.662028	63.662028	63.662028	63.649816
1.7741517	63.662025	63.662025	63.662025	63.630047
1.9266971	63.662011	63.662011	63.662011	63.645975
2.0797650	63.662019	63.662019	63.662019	63.634277
2.2323524	63.662009	63.662009	63.662009	63.648773
2.3853151	63.662012	63.662012	63.662012	63.644992
2.5264256	63.662012	63.662012	63.662012	63.644989
2.6775622	63.662058	63.662058	63.662058	63.579117
2.8320720	63.662009	63.662009	63.662009	63.648748
2.985034	63.662012	63.662012	63.662012	63.644988
3	63.662002	63.662002	63.662002	63.658890

As depicted in Figure 10, it is shown that Motor 4 has some error data concerning the set point. The setpoint value is 63,662 RPM. Then for the root mean square error is formulated in equation 18. Based on equation 18, it is found that the RMSE of Motor 4 is 2.680.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(x_i-\widehat{x_i})^2}{N}} \quad (18)$$

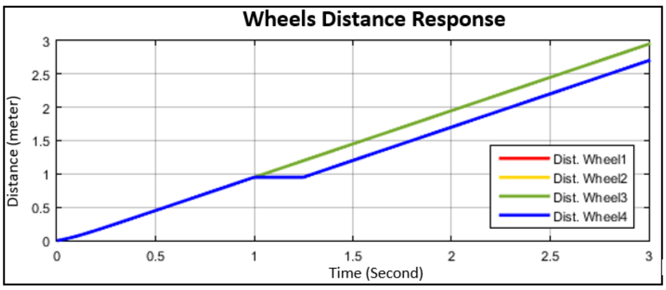

Figure 11. Wheels distance response

The next parameter that is analyzed is the wheel's distance. Figure 11 shows how the response of the wheel distance. The experience of each wheel *concerning the* slip effect. As shown in Figure 11, *a wheel* has *a* different response *concerning* the other. The blue line represents the fourth wheel. The different response means that the wheel is experiencing a slip. Meanwhile, *they have the same response for the other wheels and* don't experience the slip phenomenon.

Then for the next experiment is analyzing the slip phenomenon concerning the odometry of the robot. Figure 12 describes the result. As illustrated in Figure 12, the robot's odometry is represented by the robot's position in x – y coordinate. As shown in Figure 12, the value of the y coordinate is not always 0. Meanwhile, the robot's true condition moves straight along the x variable axis (the y variable value of the y coordinate should constantly be 0). The y variable value has a deviation of up to 5 cm away when the slip phenomenon occurs.

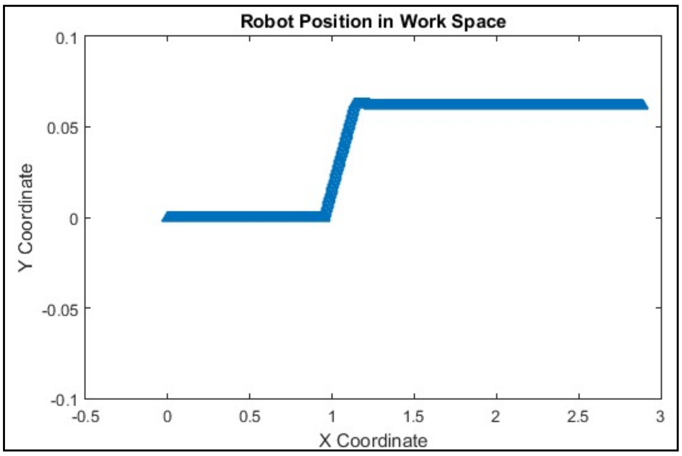

Figure 12. Robot position concerning slippage phenomenon

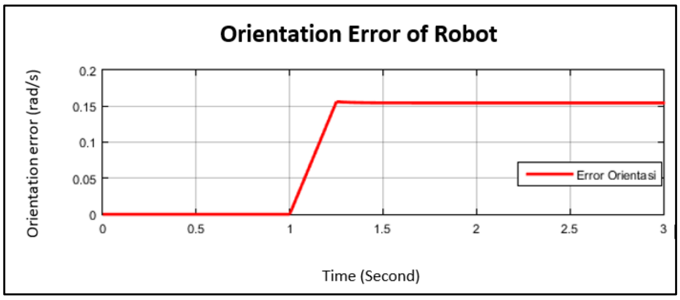

Figure 13. Robot orientation error

TABLE II
SAMPLE OF ROBOT POSITION DATA

Time (Second)	Position X (Meter)	Position Y (Meter)	Orientation Reference	Error Orientation
3.155E-30	3.159E-57	0	0	0
0.1272278	0.0893554	0	0	0
0.2797668	0.2325576	0	0	0
0.4323865	0.3835703	0	0	0
0.5854305	0.5363379	0	0	0
0.749891	0.7007497	0	0	0
0.9029303	0.853782	0	0	0

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Time (Second)	Position X (Meter)	Position Y (Meter)	Orientation Reference	Error Orientation
1.0272355	0.9712874	0.0067986	-0.0169965	0.0169965
1.1794486	1.085447	0.0448518	-0.1121295	0.1121295
1.4120825	1.3010042	0.0619284	-0.154821	0.154821
1.7181022	1.6071278	0.0618245	-0.1545613	0.1545613
1.8700789	1.7591069	0.0618221	-0.1545554	0.1545554
2.0231691	1.9121976	0.0618217	-0.1545542	0.1545542
2.1758943	2.0649228	0.0618216	-0.154554	0.154554
2.3287401	2.2177686	0.0618216	-0.154554	0.154554
2.4817792	2.3708078	0.0618216	-0.1545539	0.1545539
2.6345035	2.523532	0.0618216	-0.154554	0.154554
2.7873492	2.6763777	0.0618216	-0.154554	0.154554
2.9403883	2.8294169	0.0618216	-0.1545539	0.1545539
3	2.8890285	0.0618216	-0.1545541	0.1545541

The next factor that is analyzed when the slippage phenomenon occurs is the robot orientation error. Figure 13 describes the orientation error of the robot. As illustrated in Figure 13, the robot orientation error starts occurring after 1 second of running. The error achieves up to 0,15 rad/s. The orientation error happened when the slip occurs, and there is not slip control applied in the system. Figure 12 and Figure 13 are taken from 1303 data. The table which represents the data in 20 samples is in Table II. Based on equation 18, the RMSE for this experiment is 0.03799.

D. The System Applied Slip Control

In this experiment, the system testing applied slip control. With the same parameters analyzed with the System Without Slip Control experiment, we will see different results.

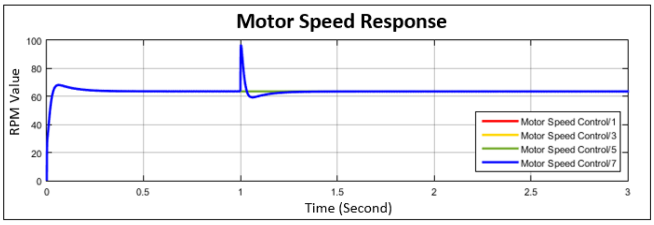

Figure 14. Motor speed response graphic using slip control

Firstly, regarding the motor speed response. By applying the slip control, the result is illustrated in Figure 14. Figure 14 tells that all of the wheels respond concerning the RPM value parameter's slip phenomenon. As seen in Figure 14, the fourth wheel (Motor 4) is experiencing RPM's deviation value for 0,1 second (after 1-second timing). Meanwhile, for the other spins, their response is as expected, although the slip phenomenon occurred. Only the fourth wheel contributed the deviation value. Figure 14 is consists of 1308, from 0 to 3 seconds for the time. Then if it is sampled into 20 of 1308 data, the result is presented in Table III. With the same setpoint value of the one that does not use the slip control, and by applying the RMSE, it is found that the RMSE is 1.339.

TABLE III
SAMPLE OF MOTOR SPEED RESPONSE USING SLIP CONTROL DATA

Time (Second)	Motor 1 (RPM)	Motor 2 (RPM)	Motor 3 (RPM)	Motor 4 (RPM)
3.1E-30	1.2E-25	1.2E-25	1.2E-25	1.2E-25
0.12014	66.3022	66.3022	66.3022	66.3022
0.26833	64.2160	64.2160	64.2160	64.2160
0.42118	63.8107	63.8107	63.8107	63.8107
0.57389	63.7202	63.7202	63.7202	63.7202
0.72695	63.7356	63.7356	63.7356	63.7356
0.87979	63.7286	63.7286	63.7286	63.7286
1.00435	63.6620	63.6620	63.6620	95.8573
1.15363	63.6620	63.6620	63.6620	61.9277
1.30658	63.6620	63.6620	63.6620	63.3443
1.45981	63.6619	63.6619	63.6619	63.5361
1.61272	63.6619	63.6619	63.6619	63.5488
1.76474	63.6619	63.6619	63.6619	63.6436
1.91783	63.6619	63.6619	63.6619	63.6213
2.07094	63.6619	63.6619	63.6619	63.5629
2.22353	63.6619	63.6619	63.6619	63.5977
2.37593	63.6619	63.6619	63.6619	63.6372
2.52902	63.6619	63.6619	63.6619	63.6004
2.68124	63.6619	63.6619	63.6619	63.65
3	63.662	63.662	63.662	63.6596

Secondly, about the wheel's distance response using the slip control. The graphic response is illustrated in Figure 15. The four wheels have the same response. All four wheels perform uniformly although the slip occurred during the experiment. No one of the wheels contributes to the deviation value of the robot distance.

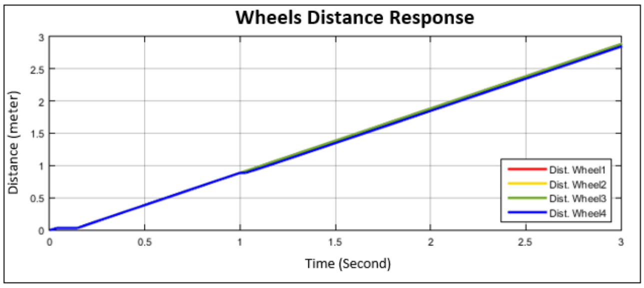

Figure 15. Wheels distance response using slip control

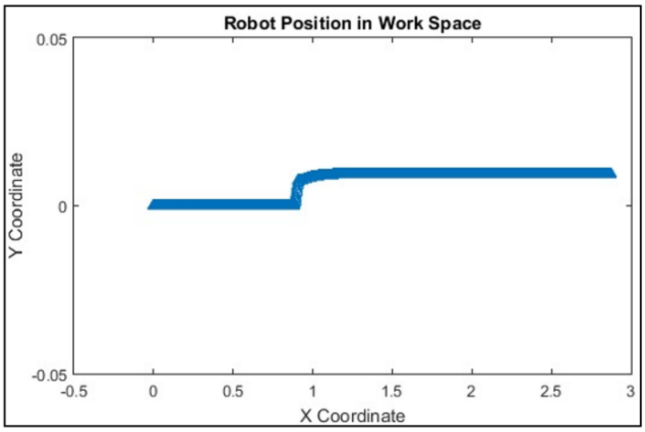

Figure 16. Robot position concerning slippage phenomenon using slip control

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Third, regarding the odometry of the robot. When the system applies slip control, the result is shown in Figure 16. The robot's position in the x-y coordinate when the system was using the slip control. Based on Figure 16, the y variable value has a deviation value of not more than 0.05 meter. The last is regarding the orientation of the robot. The graphic response is depicted in Figure 17. Figure 17 shows that the orientation error of the robot raises when the time is after 1 second. The error achieves less than 0.03 rad/s. For the data of Figure 16 and Figure 17, they consist of 1308 data during 0 up to 3 seconds, represented in Table IV. But Table IV only represents the 20 data. By using equation 18, the RMSE of this experience is 0.0060.

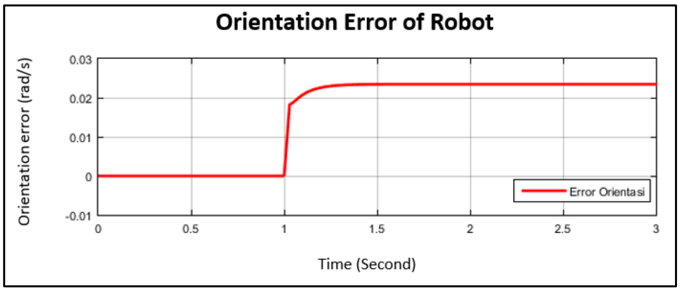

Figure 17. Robot orientation error using slip control

TABLE IV
SAMPLE OF ROBOT POSITION DATA

Time (Second)	Position X (Meter)	Position Y (Meter)	Orientation Reference	Error Orientation
3.155E-30	3.159E-57	0	0	0
0.1201472	0.0297522	0	0	0
0.2723005	0.1585689	0	0	0
0.4299344	0.3167258	0	0	0
0.5879128	0.474789	0	0	0
0.7449291	0.6318192	0	0	0
0.9033389	0.7902306	0	0	0
1.0296622	0.9091499	0.007405088	-0.0185127	0.0185127
1.1872549	1.0651504	0.008997348	-0.0224934	0.0224934
1.3440035	1.2215667	0.009329676	-0.0233242	0.0233242
1.5015434	1.379052	0.009384206	-0.0234605	0.0234605
1.6595837	1.5370837	0.009392901	-0.0234823	0.0234823
1.8163793	1.6938777	0.009394507	-0.0234863	0.0234863
1.9744263	1.8519246	0.009394603	-0.0234865	0.0234865
2.1319285	2.0094267	0.009394626	-0.0234866	0.0234866
2.2887661	2.1662642	0.009394784	-0.023487	0.023487
2.4467655	2.3242637	0.009394655	-0.0234866	0.0234866
2.6038471	2.4813452	0.009394766	-0.0234869	0.0234869
2.7612539	2.638752	0.009394791	-0.023487	0.023487
3	2.8774981	0.009394822	-0.0234871	0.0234871

IV. CONCLUSION

Based on the experiment between applying and not applying the slip control, it can be concluded. Motor speed response without using slip control has a more significant Root Mean Squared Error (RMSE). The RMSE for the experiment without applying slip control is 2.680. Meanwhile, for the investigation, by using slip control is 1.3393.

Regarding the robot position (odometry of the robot), the system applying slip control produces a smaller RMSE—the one which is not using slip control yields RMSE 0.0379. Meanwhile, for the system which applying slip control, producing RMSE 0.0065.

Then for the robot's wheels distance response, the system that is applying the slip control produces less deviation value. The one that does not use slip control is experiencing the fourth wheel's deviation value, about 0.25 meters. Meanwhile, the deviation value is 0 meters for all wheels for the system that is applying the slip control.

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