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

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Abstract— Slip on the mobile robot has a big 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 analysed is the accuracy of motor speed and the accuracy of robot position when the robot is moving. The result shows that the Root Mean Squared Error (RMSE) for the motor speed performance that does not using slip control is 2.680, meanwhile for the system using slip control produces RMSE 1.3393. Regarding for the robot position accuracy, the RMSE of the system which does not use slip control is 0.0379, meanwhile for the system which 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 the fields of industry, defense and security, transportation, and the others. So that research on mobile robots is still developing today, as explained by Pandey, *et al*, in [1]. There are various problems found in the issue of mobile robots, one of them is maneuverability. Lucet, *et al*, in [2] experienced problems in the mobile robot maneuvering experiment. The resulting precision reaches an error of approximately 15 degrees using a speed of 8 m / s.

The mobile robot with omni-directional drive has the advantage of maneuvering because of the unique structure of the wheels, 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 Lyong, *et al*, in[3]. This capability is due to the fact that the mobile robot is equipped with wheels that have 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.

Ribiero, *et al*, in [4] used an omni wheel on a mobile robot with an omni-directonal drive which is implemented in fast movement. The omni wheel has simple control and steering but has limited traction. This affects the slip phenomenon. Ping, *et al*, in [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. In addition, slip also 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 motion precision level of the mobile robot 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 or 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. To 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 so that slippage can be avoided.

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

II. Research Methodology

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

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 mobilerobot with the omnidirectional wheels, the configuration is depicted in the Figure 1.

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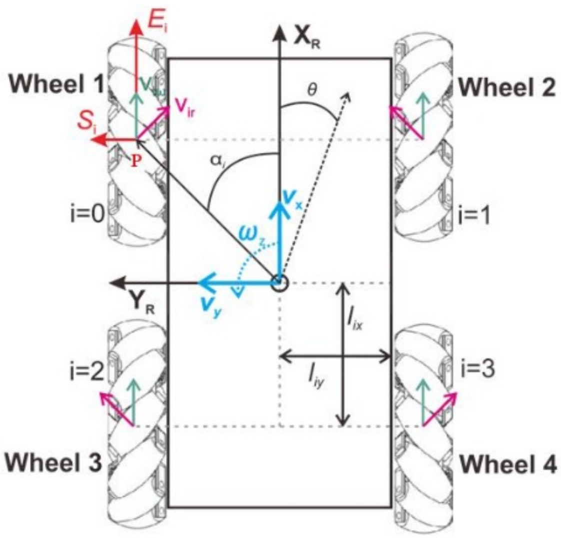

Figure 1. Mechanical design of omnidirectional wheels

Taheri H., *et al,* explained in [6] regarding the kinematics of omniwheel configuration which depicted in Figure 1. i is the index of wheels. v_x and v_y are robot linear velocity 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 with respect to the wheel revolutions, ($i = 0,1,2,3$) 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 base frame of mobile robot, the Cartesian coordinate. θ is the orientation angle. l_{ix} is a half of the distance between front wheels and l_{iy} is a half of distance between front wheel and rear wheel.

The configuration of the wheel is ilustrated in Figure 2.

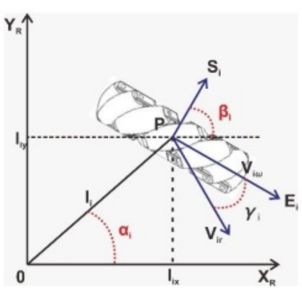

Figure 2. Wheel configuration in the robot frame

Based on Figure 2 and Figure 1, the wheel velocity (center point) with respect to the frame X_ROY_R is described as follow,

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

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

With ${}^{p_i}T_R$ is the transformation matrix which calculated from the i-th center of the wheels with respect to the robot coordinate system.

Because the motion of the robot is planar motion, then it determines,

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

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

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

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,

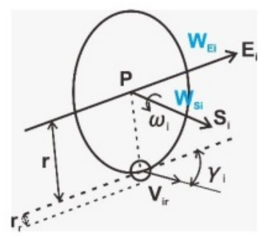

Figure 3. The i-th wheel configuration

The v_{ir} is the velocity of i-th wheel with respect to 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 as follow 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 below,

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

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

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 and equation 3, it can be obtained that,

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

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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 velocity (ω_i) of *i*-th wheel, it can be derived as following,

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

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

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

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 following,

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

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 below,

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

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

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. There are many methods that 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 [7] and Tzou, *et al*, in [8].

Shih-an Li, *et al*, in [9] 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, especially when the motor rotates in the opposite direction repeatedly. The architecture of the motor control is illustrated in Figure 4.

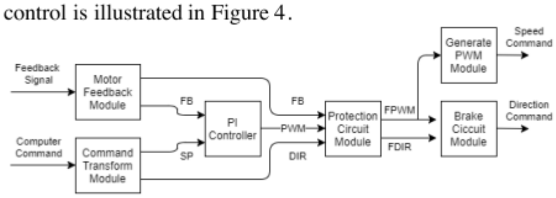

Figure 4. The architecture of DC Motor velocity controller

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 occurrence of 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.

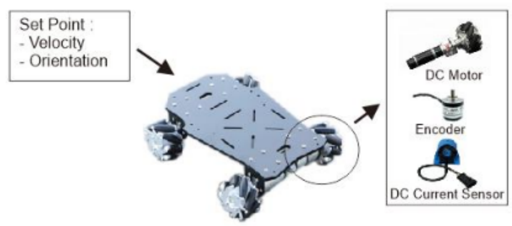

Figure 5. The mobile robot configuration

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

The DC motor rotation is regulated using the Pulse Witdh Modulation (PWM) technique so that it allows 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 touch point of the wheel to the floor surface is very small and the touch point 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 regarding the control of motor DC using slip estimation based on observer.

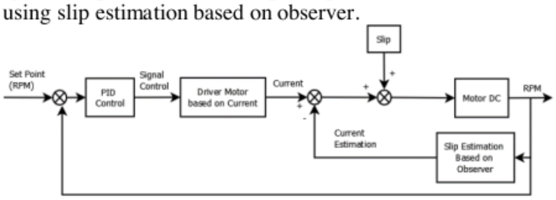

Figure 6. The control of motor equipped with slip estimation

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By using the set point of angular velocity (RPM), it will be processedd using PID control such that the signal control is produced. PID control is used to adjust the speed of the DC motor in real time to match a given set point. the output of PID control (sigal control) will be processed into driver motor based on current.

Then the output (current) equipped with the slip estimation is calculated. Beside the current from the driver motor output, the current estimation from observer is calculated.

The current estimation becoming a feedback in this system. The feedback is the result of slip estimation based on observer. The output of the system is RPM that has been added the slip control estimation. The process will be looped ntil it is in accordance with the specified RPM set of points.

III. Result and Discussion

The results consist of three parts. The experiment regarding the speed of DC motor 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 in accordance with the RPM setpoint value given. Then observe the response of the motor whether the motor speed is able to equal or near to the given RPM setpoint, and can maintain motor rotation if there is a disturbance (briefly held). By using combination values between RPM speed and PID value (Kp, Ki and Kd), the results are discussed as follow,

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.

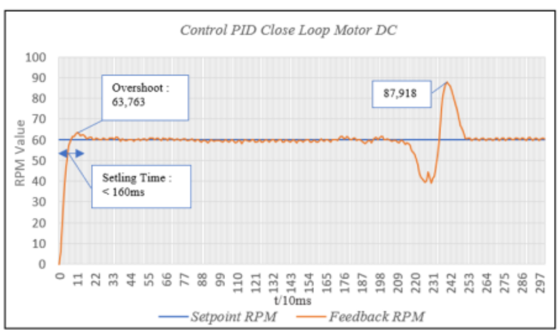

Figure 7. The PID response graphic for RPM 60

Figure 7 is a graph produced by the movement of the motor when the set point 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. Then 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 and there is a value of RPM achieved 87.918 RPM.

Then the next experiment is when the RPM value is set to be 180. the result is shown in Figure 8.

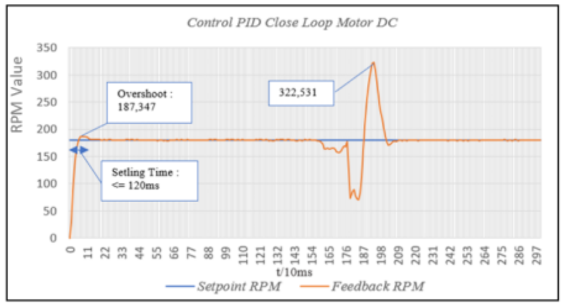

Figure 8. The PID response graphic for RPM 180

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. Then 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 and there is a value of RPM achieved 322.351 RPM.

The next RPM given is 360. The response is iustrated in Figure 9.

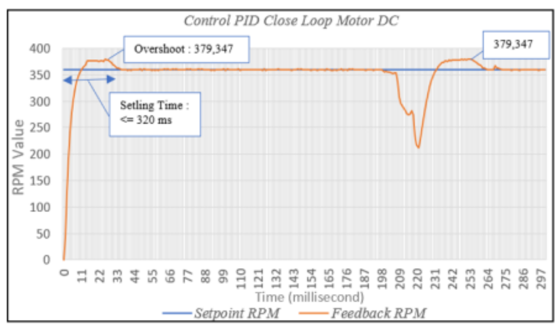

Figure 9. The PID response graphic for RPM 360

Based on Figure 9, it takes less than 320 millisecond for the system to achieve the settling time. Then for the overshoot, the system achieves 379.347 RPM. Meanwhile when the motor is being held for a while (as the disturbance), the PID control system needs around 76 millisecond to still stich to the set point value. Although in the process, it is also happend the RPM value about 379.347.

B. System without Slip Control

The system testing is carried out without using a slip control, this causes the slip phenomenon effect. Some of the things that

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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 RPM value that is illustrated in Figure 10.

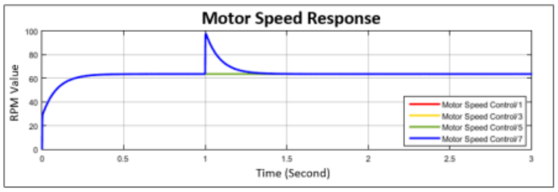

Figure 10. Motor speed response graphic

In the omni mechanum, 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 effects to the RPM which suddenly rises and then falls back to the initial RPM. The deviation of RPM value occurs during 0.25 second. The Figure 10 is tested with 1303 data from 0 up to 3 second. Then it is presented with 20 samples data in Table I.

TABEL 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 with respect to the set point. The set point value is 63,662 RPM. Then for the root mean square error is formulated in equation 18,

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

Based on equation 18, it is found that the RMSE of Motor 4 is 2.680.

The next parameter that is analysed is the wheels distance. Figure 11 shows how the response of the wheel distance.

Figure 11. Wheels distance response

Figure 11 tells the experience of each wheel with respect to slip effect. As shown in Figure 11, there is a wheel that has different response with respect to the other. The blue line represents the fourth wheel. The different response means that the wheel is experiencing a slip. Meanwhile for the other wheels, they have the same response and they don't experience the slip phenomenon.

Then for the next experiment is analysing the slip phenomenon with respect to the odometry of the robot. Figure 12 describes the result,

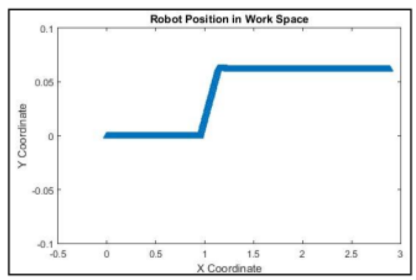

Figure 12. Robot position with respect to slippage phenomenon

As ilustrated in Figure 12, that the odometry of the robot is represented by the robot position in x – y coordinate. As shown in Figure 12 that the value of y coordinate is not always 0. Meanwhile the true condition is the robot moves staright along x axis (the y value of y coordinate should be constantly 0). The y value has a deviation of up to 5 cm away when the slip phenomenon occurs.

The next factor that is analysed when the slipage phenomenon occurs is the robot orientation error. Figure 13 describes the orientation error of robot.

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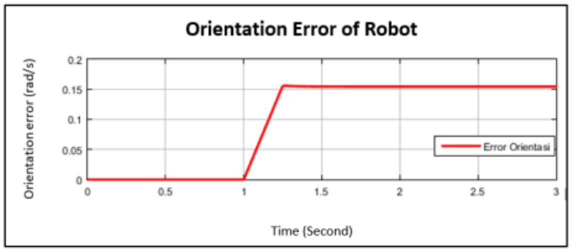

Figure 13. Robot orientation error

As described by Figure 13, the robot orientation error starts occurring after 1 second 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.

TABEL 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
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

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 that is analysed with *System Without Slip Control* experiment, we will see the different result.

Firstly, regarding the motor speed response. By applying the slip control, the result is ilustrated in Figure 14.

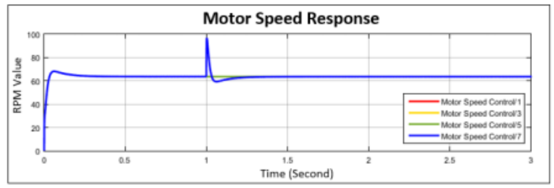

Figure 14. Motor speed response graphic using slip control

Figure 14 tells that all of the wheels response with respect to the slip phenomenon in RPM value parameter. As seen in Figure 14, the fourth wheel (Motor 4) experiencing the deviation value of RPM for 0,1 second (after 1 second timing). Meawhile for the other wheels, their response is as expected although the slip phenomenon occured. Only fourth wheel that contributed the deviation value.
Figure 14 is consists of 1308, from 0 to 3 second for the time. Then if it is sampled into 20 of 1308 data, the the result is presented in Table III,

TABEL 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

With the same set point 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.

Secondly, about the wheels distance response using the slip control. The graphic response is ilustrated in Figure 15.

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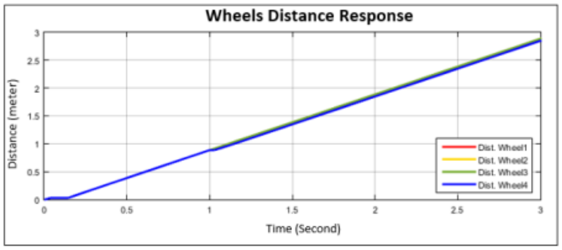

Figure 15. Wheels distance response using slip control

By reading from Figure 15, the four wheels have the same response. All of four wheels perform uniformly although the slip occured during the experiment. no one of the wheels which contributes for the deviation value of the robot distance

Third, regarding the odometry of robot. When the system applies slip control, the result is shown in Figure 16.

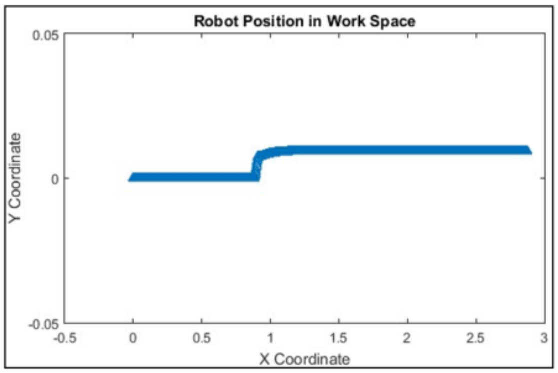

Figure 16. Robot position with respect to slippage phenomenon using slip control

Figure 16 shows how is the robot position in x-y coordinate when the system applying the slip control. Based on Figure 16, the y value has deveiation value not more than 0.05 meter. The last is regarding the orientation of robot. The graphic response is depicted in Figure 17.

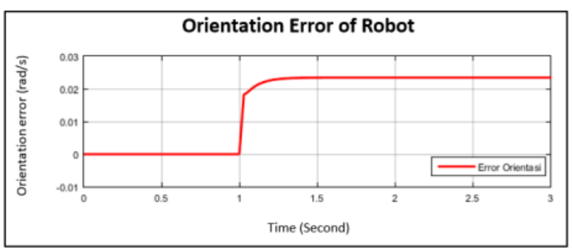

Figure 17. Robot orientation error using slip control

Figure 17 shows that the orientation error of the robot raises when the time is after 1 second. The error achieve 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 second which represent in Table IV. But Table IV only represent the 20 data.

TABEL 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

By using equation 18, the RMSE of this experience is 0.0060.

IV. CONCLUSION

Based on the experiment between applying and not applying the slip control, it can be concluded that,

Motor speed response without using slip control has bigger Root Mean Squared Error (RMSE). The RMSE for experiment without applying slip control is 2.680. Meanwhile for the experiment by applying slip control is 1.3393.

Regarding for the robot position (odometry of robot), the system which is applying slip control produces 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 wheels distance response of the robot, the system that is applying the slip control produces less deviation value. The one that is not applying slip control experiencing the deviation value for the fourth wheel about 0.25 meter. Meanwhile for the system that is applying the slip control, the deviation value is 0 meter for all wheels.

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