

# 2020

*by* Ratih Kumalasari

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**Submission date:** 11-Apr-2022 07:33AM (UTC+0700)

**Submission ID:** 1807093830

**File name:** Evita\_2020\_J.\_Phys.\_Conf.\_Ser.\_1572\_012016.pdf (1.56M)

**Word count:** 3447

**Character count:** 18620

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To cite this article: M Evita *et al* 2020 *J. Phys.: Conf. Ser.* **1572** 012016

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## 7 Development of a robust mobile robot for volcano monitoring application

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**Abstract.** Indonesia is one of the countries that lies in the pacific ring of fire, the highlighted area that known to be active by seismic and volcano activities. Indonesia has a total of 129 active volcanoes that make the land fertile, but also vulnerable to disaster. When a volcanic eruption occurs, the current fixed monitoring system is not fully reliable. On the other hand, monitoring of further volcano activities is critically needed in this situation. Therefore, a volcano monitoring system that can move freely and controlled safely is needed. To solve this problem, a mobile robot that capable of moving in volcano area has been developed. The robot locomotion system is designed with 2 DC motor using 4-wheel drive configuration. Each motor implements a PID Controller to adjust the speed that has been set. In addition, the robot is also equipped with a camera (Logitech C920), vibration sensor (ADXL 345), temperature sensor (DHT 11), carbon dioxide gas sensor (MG-811), and sulphur dioxide gas sensor (TGS 2602) to retrieve volcanic condition data, as its function for volcano monitoring. The microcontroller used to adjust motor control and read sensors data is Nucleo STM32-F466RE, while the mini-PC that being used for integrated data communication and processing is Raspberry PI 3B+. PID Controller has been successfully applied with average deviation of 2.5% for the left motor, and 2.75% for the right motor.

### 1. Introduction

Volcano is a geological environment which has 3 important elements: magma, eruption and certain structure [1] Borgia A 2010 What is a Volcano? The Geological Society of America Special Paper 470. In the world volcano history, there were 10 biggest eruptions recorded where the two of them happened in Indonesia: Tambora Volcano in 1815 (80.000 casualties) and Krakatau in 1883 (36.000 casualties) [2]. Currently, Merapi is the most active volcano in Indonesia which erupts on every 2 to 5 years, while surrounded by dense population in the middle of Java island [3]. These volcanoes and 126 other active volcanoes [4] lie on the Asia Pacific ring of fire where seismic activities frequently happened [5].

Volcano in Indonesia is divided into 3 types by The Centre of Volcanology and Geological Hazard Mitigation (Pusat Vulkanologi dan Mitigasi Bencana Geologi) according to their type of eruption: type A (79 volcanoes) has been erupted since 1600, type B (29 volcanoes) has been erupted before 1600 and type C (21 volcanoes) is contained solfatara and fumaroles inside and around its crater [6][7]. The



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objective of this classification is for hazard mapping of mitigation process. This map could be arranged times before the eruption by a volcano early warning system as we have been developed [8-16].

The system consists of two modes, when there is no emergency, it is set to normal or fixed mode of field sensor nodes, however when some activities arise, then eruption take places that leads to a terrific disaster, a mobile mode (fixed-node and teleoperated mobile robot combination) is activated to monitor and acquire physical parameter of the erupting volcano [8-16].

Mobile robot has been used for volcano exploration and observation in some researches [17-20]. A giant Unmanned Ground Vehicle (UGV) or usually called mobile robot, named Robovolc was developed in Europe around 2003 [17]. Robovolc, an articulated frame robot [21] categorized as wheeled robot [22] consumed relatively low power, could be controlled flexibly, however its mobility was limited by its big size [23].

In 1999, NASA and Carnegie Melon University developed a legged robot for volcano exploration called Dante II [19]. This robot had wider mobility due to its flexible locomotion imitates living cockroach [22]. Dante II successfully walked 165 m of a volcano while avoiding 1 m height of an obstacle, although it moved very slow because its complex architecture [19].

Nagatani reported his work about wheeled mobile robot in 2014 [20]. The non-articulated frame robot called CLOVER was designed for volcano exploration with bigger wheels than its body to prevent movement problems due to its permanent shape and locomotion.

Another type of mobile robot according to its locomotion is tracked robot [22]. The Robhaz DT3 and DT5 developed by KIST Intelligent Robotics Research Centre is one of them [24]. Although this robot could be applied for volcano exploration, it moved slower and consumed more power than any other types of robots [22].

Therefore, in this research we have developed our 4-wheeled mobile robot called PRAWIRA (an acronym from *Perangkat Kendaraan Tanpa Awak untuk Wilayah Rawan – Unmanned Vehicle for Hazard Application*) for volcano exploration and monitoring. To solve the limited movement problem, it is combined with an Unmanned Aerial Vehicle (UAV) for transport mode when there is no physical parameter acquired by the robot.

## 2. Mobile robot design

Kinematics of 4 wheel drive robot

PRAWIRA has been designed with skid-steering control method for 4-wheel drive robot. Robot navigation with skid-steering is concentrated on right and left sides motor connected with pulleys and belts relative velocities. This robot has high manoeuvre, able to move forward, backward, turn to right or left in all terrain by controlling its velocity [25]. Furthermore, the simple yet robust mechanical structure, provides wider space for robot equipment [26].

Kinematics model for skid-steering mobile robot will be explained here (Fig. 1). Robot velocity vector (with  $\omega = \dot{\psi}$ , where  $\psi$  is orientation of robot reference frame, or angle between  $X'$  and  $X$  axis, where  $(X, Y)$  is inertial reference frame and  $(X', Y')$  is robot reference frame with the centre of the mass is in origin (0,0)) is formulated as  $\dot{\mathbf{q}} = [\dot{x} \ \dot{y} \ \dot{\psi}]^T$ , where  $(x, y)$  is position of the centre of the mass from the inertial frame.

Skid Steering Mobile Robot (SSMR) has non-zero lateral velocity,  $v_{iy'}$  causes a nonholonomic constraint:

$$v_{iy'} = x'_{CIR} \dot{\psi}, \quad (1)$$

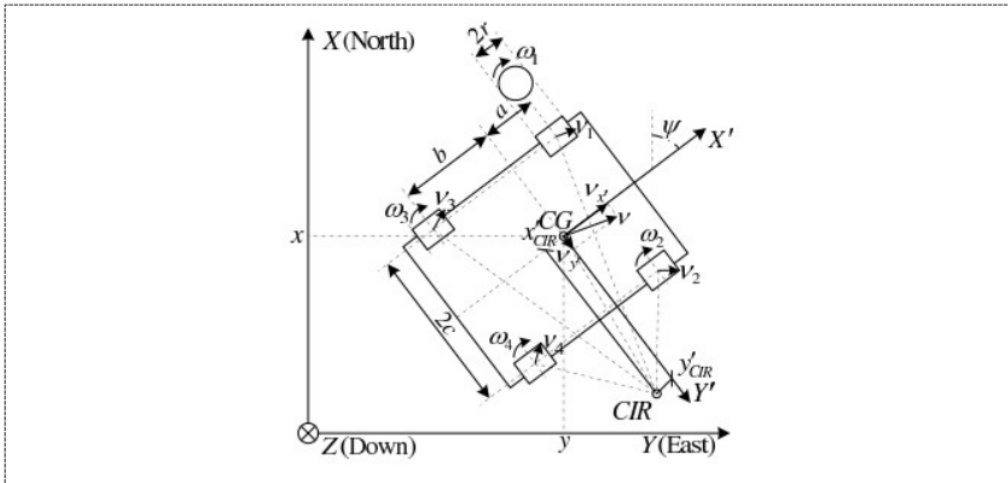


Figure 1 Geometry for Skid-Steering Robot [27]

where

$$x'_{CIR} \in (-b, a) \quad (2)$$

where  $(X'_{CIR}, Y'_{CIR})$  is instantaneous centre of rotation (CIR),  $a$  is distance from centre of the mass to the front wheel in  $X'$  axis, while  $b$  is distance from centre of the mass to the rear wheel in the same axis. Thereupon, velocity  $\dot{\mathbf{q}}$  is represented by

$$\dot{\mathbf{q}} = S(\mathbf{q})\boldsymbol{\eta}, \quad (3)$$

where

$$S(\mathbf{q}) = \begin{bmatrix} \cos \psi & -x'_{CIR} \sin \psi \\ \sin \psi & x'_{CIR} \cos \psi \\ 0 & 1 \end{bmatrix} \quad (4)$$

and

$$\boldsymbol{\eta} = \begin{bmatrix} v'_x \\ \omega \end{bmatrix} \quad (5)$$

<sup>11</sup>  $S(\mathbf{q})$  is a full rank matrix, where the column is in null space of  $A(\mathbf{q})$  the robot's state with the constraint, or

$$S^T(\mathbf{q})A^T(\mathbf{q}) = \mathbf{0} \quad (6)$$

Robot DC motor controller

<sup>14</sup> Direct Current motor transfer function. Direct current (DC) motor converts electrical energy into mechanical energy using two magnetic fields, from pole assembly and current flowing the motor wire,

hence the torque rotates the motor (Fig.2). Therefore, angular velocity of DC motor could be controlled easier than the AC motor by controlling the input voltage [28].

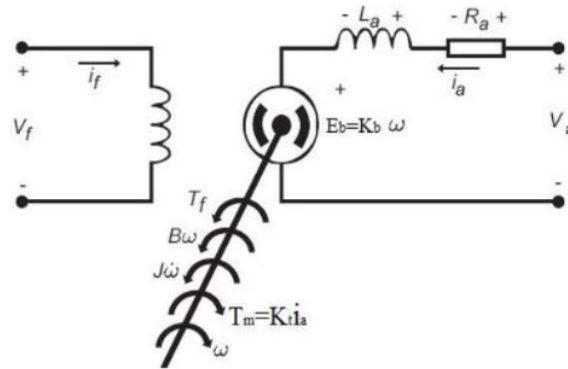


Figure 2 Direct current motor [28]

Shaft rotor angular velocity and input voltage are related by a transfer function in frequency domain  $s$ :

$$G(s) = \frac{\omega(s)}{V_a(s)} = \frac{K_t}{JL_a s^2 + (JR_a + BL_a)s + (K_t K_b + BR_a)} \quad (7)$$

where,  $K_t$  = torque constant (Nm/A) and  $K_b$  = back emf constant (Vs/rad)

Equation (7) is a continuous transfer function for input voltage reference control parameter. However the discrete is used in this research for more practical analysis.

#### PID Controller

Proportional-Integral-Derivative (P, I, D) controller often uses in industry because of its simple structure and good performance for DC motor controlling [29] compare to other controllers: Fuzzy Algorithm, Bangbang Control, Linear Quadratic Integrator, Feedforward Control, etc. In this research, P, I, D constants had been simulated before the motor controlled by the controller. PID control function is formulated in Eq (8).

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt} \quad (8)$$

where  $K_p$ ,  $K_i$  and  $K_d$  (positive constants) are correction factors for P, I and D.  $K_p$  is an error correction for P controller for responding the proportional error.  $K_i$  is an error correction for I controller for cutting the offset in steady state and damping the oscillation, while  $K_d$  is for D controller in future error prediction.

### 3. Result and Discussion

#### Mobile Robot Implementation

PRAWIRA mobile robot (total mass 7 kg with symmetrical body frame) has been developed in 450 x 445 x 220 mm dimension of length, width and height for the robot electrical components. The symmetrical frame was designed for continuous mobility when robot flipping over because of the uneven terrain. This frame was manufactured using light, corrosion proof, and non-toxic of 2 mm aluminum L. Other part of the frame was made from acrylic, lighter than aluminum and other metals yet firm and flexible suitable for field application. These light materials were used for the requirement where the robot should be as light as it can to be transported by the UAV. The robot is also equipped by four-22 mm diameter-wheels.



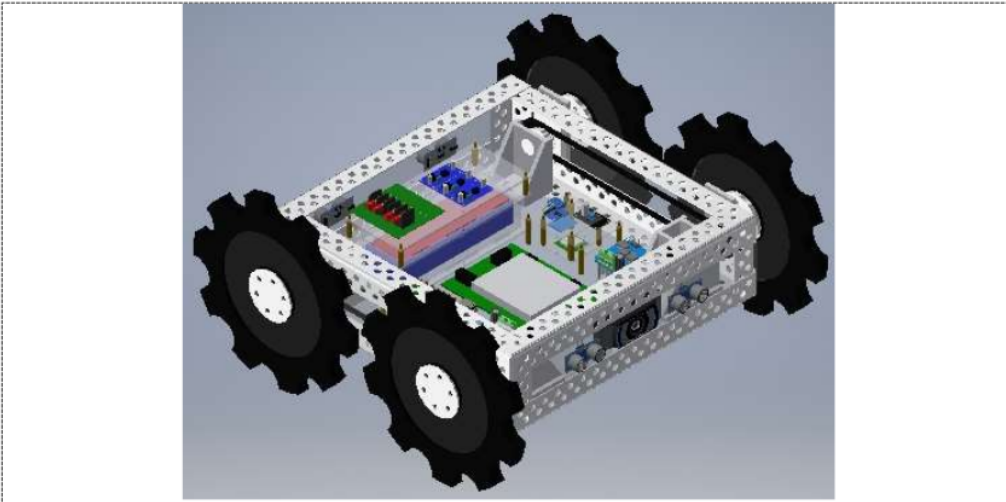


Figure 3 PRAWIRA robot 3D design

The robot was designed with bigger wheels for uneven terrain in volcano area (Fig. 3). For wheels drive mechanism is implemented by two-24 volt-DC motor (PG 28) using pulley and belt. This motors are controlled by microcontroller STM32 Nucleo F446RE as secondary controller connected the motor with main controller, while robot main controller, Raspberry Pi 3 controls DC motors velocity and PID algorithm processing. Control system diagram along with electrical wiring is presented in Fig. 4.

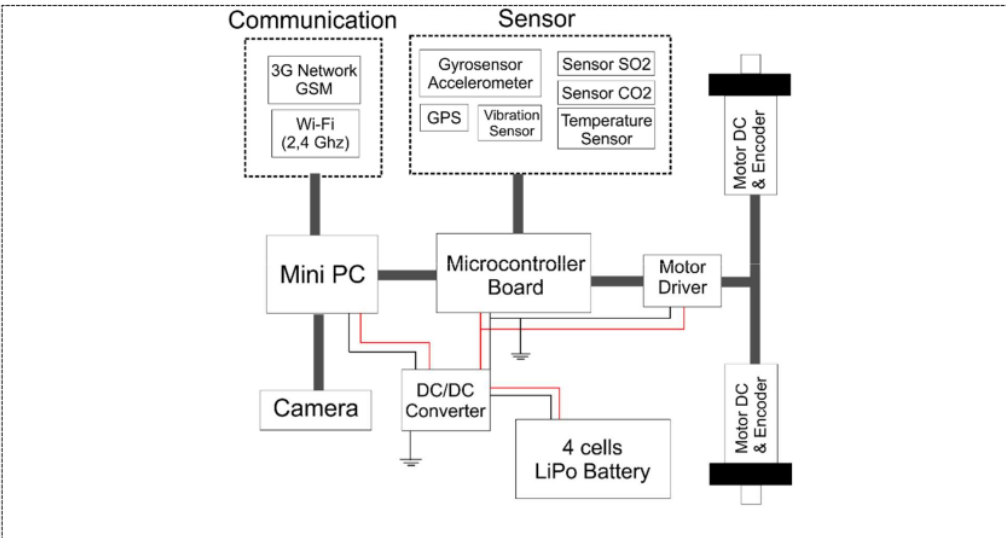


Figure 4 Control system diagram of PRAWIRA

Not only for exploration, PRAWIRA also designed for volcano monitoring. Therefore, this robot is equipped with CO<sub>2</sub> (MG-811) and SO<sub>2</sub> (TGS-2602) gas sensors, also temperature (DHT 11) and

vibration sensors (MPU 6050) (Fig. 5) for basic volcano physical parameter monitoring and volcano early warning system. Moreover, robot implementation could be seen in Fig. 6.

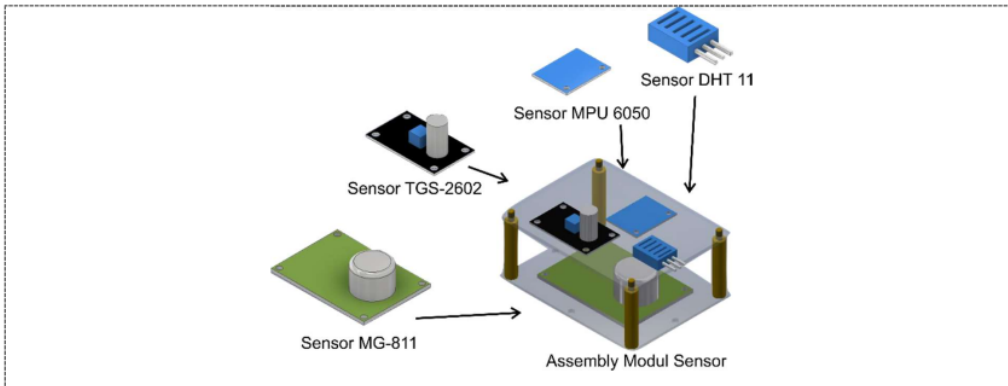


Figure 5 Volcano monitoring sensor design of PRAWIRA

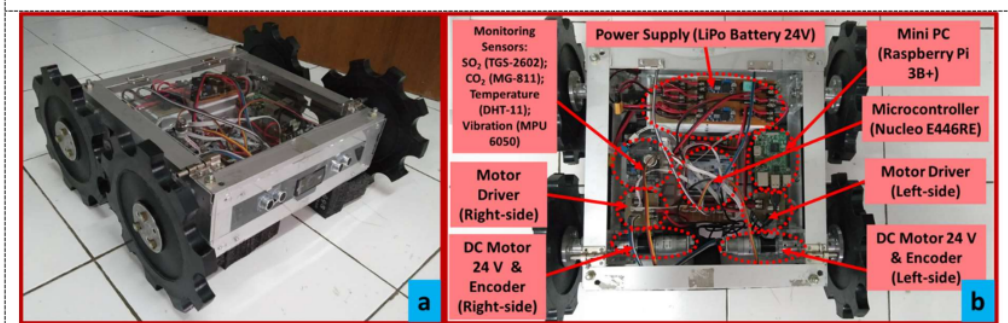


Figure 6 Mobile robot implementation from front side (a) and upside (b)

#### DC motor transfer function

Before PID control processed, transfer function (a mathematical model of motor physical condition) for each DC motor had been derived using Laplace transformation of angular velocity on input voltage of Eq. 7. Feedback data of DC motor PG 28 (537.6 impulse per rotation) from encoder of 0.05 s sampling time (of 3 s observation) using 24.77 Volt step input signal, was controlled by microcontroller ST32 Nucleo F446RE. These impulses converted into velocity (m/s) before had been transformed for mathematical model of right-side motor in discrete function  $z$ :

$$g(z)_1 = \frac{0,3301}{1-0,6698z^{-1}} \quad (9)$$

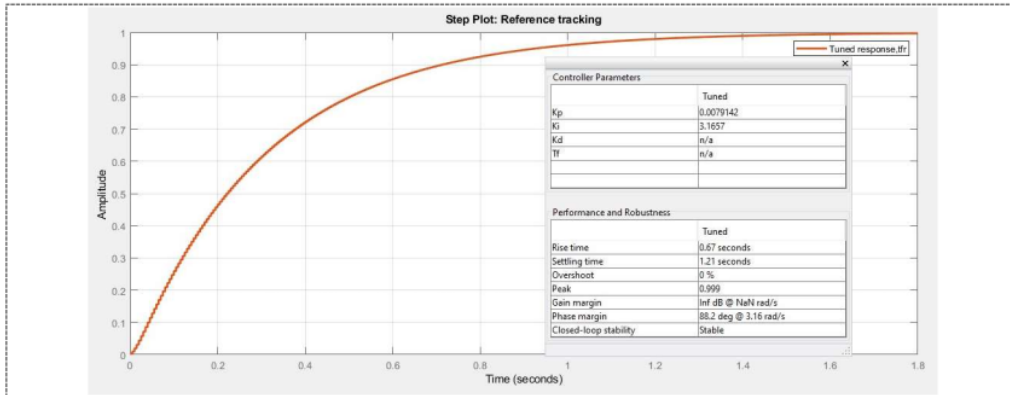
and left-side motor:

$$g(z)_2 = \frac{0,3477}{1-0,652z^{-1}} \quad (10)$$

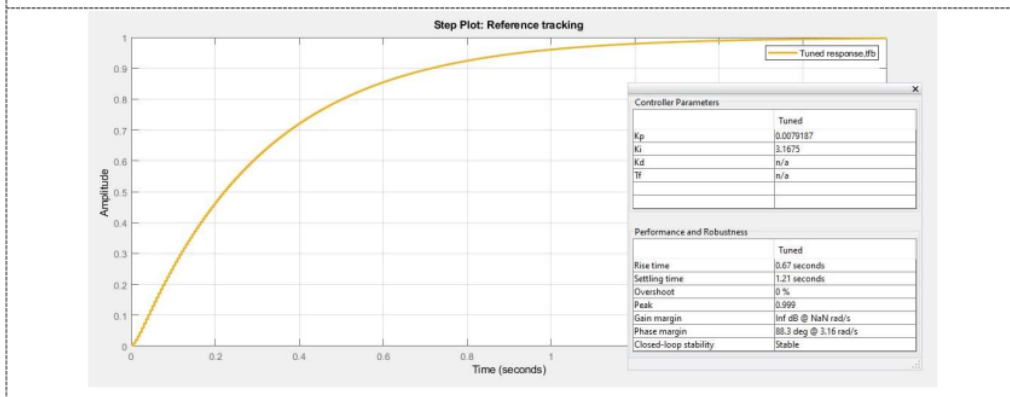


*PID control design*

Transfer functions (Eq. 9 and 10) were needed for PID tuning process by generating  $K_p$ ,  $K_i$  and  $K_d$  using P and I (without D) controller, the most stable and precise to reach the desired point of the parameter controlled even after disturbances [30]. The results are shown in Fig. 7 and 8, where system overshoot is 0% for rise time 0.67 s and settling time 1.21 s (inset tables of Fig. 7 and 8). The controller constants are represented in Table 1.



**Figure 7** PID tuning for right-side DC motor and controller parameter (the inset table)



**Figure 8** PID tuning for left-side DC motor and controller parameter (the inset table)

**Table 1** Controller constants  $K_p$ ,  $K_i$  and  $K_d$  for right and left sides motor

Motor	$K_p$	$K_i$	$K_d$
Right	0,0079142	3.1657	0
Left	0,0079187	3.1675	0

### Testing of robot controller system

Data from DC motor encoders performing PID controller for 6 m/s desired velocity in 8.95 s with 20 Hz of sampling rate can be seen in Fig. 9. Motor velocities (blue graphs of Fig. 9a and 9c) are physical motor velocities for 11 cm wheel radius, while the oranges graphs are setting point for desired velocity (6 m/s). Although there are overshoots in the beginning of both motors, PID controller compensate the motors to reach the setting point in no more than 1 second. Generally, the PID controller showed some good performances proved by only 2,55% average deviation from desired velocity for left-side motor and 2,75% from the right-side. Furthermore, Pulse Width Modulation (PWM) input (Fig. 9b and d) from microcontroller always changed adaptively to maintain the velocity at the same point.

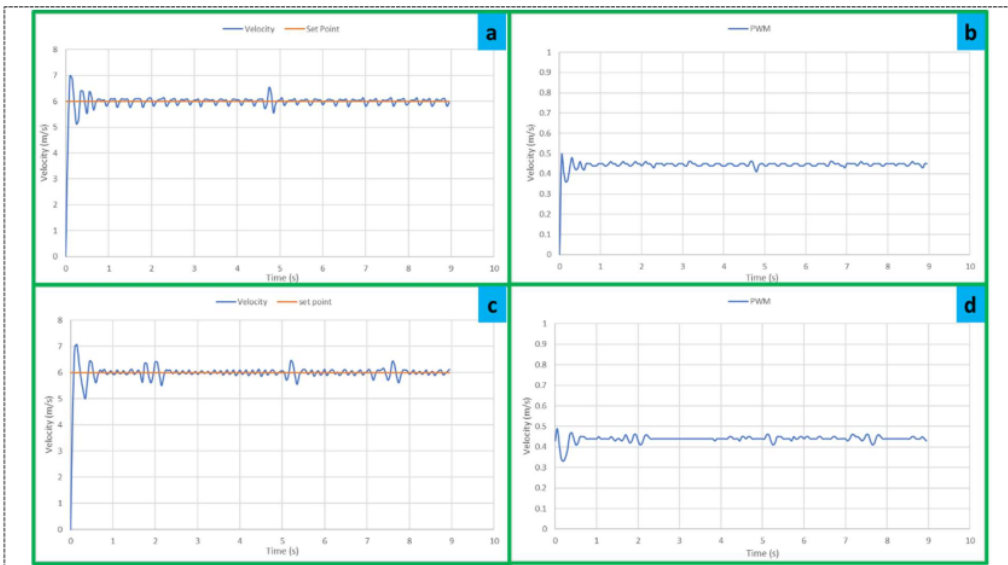


Figure 9 PID controller system implementation for right-side motor (a) the PWM response (b) PID controller system implementation for left-side motor (c) the PWM response (d)

## 4. Conclusion and Future Work

### Conclusion

A 7 kg mobile robot (450 x 445 x 220 mm of height, width and length) has been successfully manufactured with the light material of 2 mm aluminum L for transport mode purposes and 4 wheeled drive skid-steering mechanism of four-22 of diameter-wheels. It is also equipped with SO<sub>2</sub> and CO<sub>2</sub> sensors, also temperature and vibration sensors for volcano monitoring and early warning system.

The PID controller for right and left front side motors has been successfully implemented and shows satisfied result with average deviation 2.5% for the left-side and 2.75% for the right one.

### Future Work

In the near future, some tests for the robot will be conducted regarding: basic motion, monitoring sensors, control system both in laboratory and real volcano.

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#### Acknowledgments

We would like to say thank you to ITB for supporting this research through <sup>15</sup> P3MI (Program Penelitian Pengabdian Masyarakat dan Inovasi) research fund and also the head of the Electronics and Instrumentation Laboratory of Physics Department, the head of the Production Engineering Laboratory of Mechanical Engineering Department and the head of the Mechanical Workshop of Physics Department of ITB for allowing us to use the equipment for this research.

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