

Velocity measurement based on inertial measuring unit

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Abstract

Vehicles technology have been a priority area of research over the last few decades. With the increasing the use of electronic components in the automotive industry to measure conditions around the vehicle, the focus of automotive technology development is now leading to the development of active technology. Information on the speed of conventional vehicles is generally still obtained based on the rotation of the wheel, but there are weakness in the system that is the difference between wheel and road through vehicle also changes wheel radius of the vehicle due to wind tube air pressure that can change at any time. In this research used Inertial Measuring Unit (IMU) 6 axis (accelerometer and gyroscope) which have been done filtering by using Kalman filter in order to make output sensor value more stable, results obtained at the test of 0 m/s had an RMS error of 0.8696 m/s when elevation is +450; 0.0393 m/s when elevation is 00; and 0.3030 m/s when elevation is -450. this research is expected to be an exploration for the development of a decent system that is suitable to be used as vehicle speed estimator which is as reliable as it is by using an existing speedometer on a ground vehicle generally regardless of slippage and changes in wind capacity on wheels.

Keywords: inertial measuring unit, Kalman filter, velocity

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1. Introduction

Vehicles technology have been a priority area of research over the last few decades. With the increasing of electrical components in the automotive industry to sense conditions around the vehicle, the focus of automotive technology development is now leading to the development of active technology [1]. The speed information on conventional vehicles is obtained from the rotational speed of the wheels. But there is a shortage in this system which is the slip between the wheels and the road through which the vehicle passes [2]. In this study used inertial measuring unit (IMU) 6D (6 axes) consisting of 3 axes acceleration sensor and 3 axis angular velocity sensor [3-5]. This study is expected to be an exploration for the development of a viable system to use as a reliable vehicle speed estimator as well as using an existing speedometer on a ground vehicle generally regardless of slippage and changes in wind capacity on wheels [6-8].

2. Research Method

The system is designed by 3 main components consist of IMU sensor, Microcontroller and Display. The functional block diagram is shown in Figure 1. In this design desired final specifications such as the following points:

- Vehicles acceleration of 0.2-10 m/s².
- Vehicle speed of 0-140 km/hour.
- The speed rating is updated maximally within 1 meter once.
- The system can only be used on public streets

According to the Figure 1, there are 5 main blocks to obtain the velocity value:

- IMU to obtain linear acceleration value (α) and angular velocity value (ω), this section works as an Input of system.
- IMU output containing noise by using Kalman filter so that noise will be muffled.

- Integrate angle velocity value towards time by Midpoint Riemann Sum method to obtain angle position value.
- Calculate the dynamic acceleration value of a vehicle parallel to the earth's surface by using angle position value and acceleration sensor value.
- Integrate dynamic acceleration value towards time by Midpoint Riemann Sum method to obtain velocity value.
- The whole process will be repeated with t intervals.

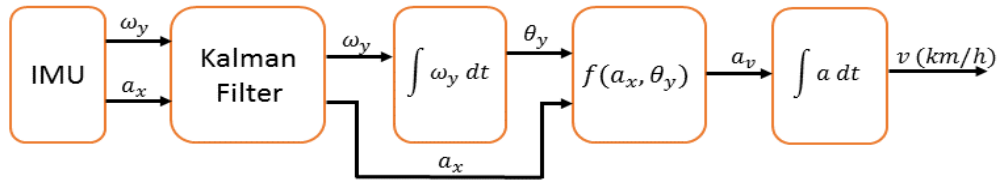


Figure 1. Functional block diagram of the system

2.1. Dynamic Acceleration

To eliminate the effect of earth gravitational acceleration, the following equations are made based on acceleration vector diagram shown on Figure 2. Obtain angle position value θ_0 (initiation value)

$$\theta_0 = \tan^{-1} \frac{g \sin \theta}{g \cos \theta}$$

$$\theta_0 = \tan^{-1} \frac{a_x}{a_y}$$

Dynamic acceleration is the acceleration value which is unaffected from the static acceleration caused by gravity of the earth, so that the readable is pure acceleration parallel to the surface of the earth [9, 10].

a = acceleration parallel to the surface of the earth

$$a = a_x - g \sin \theta$$

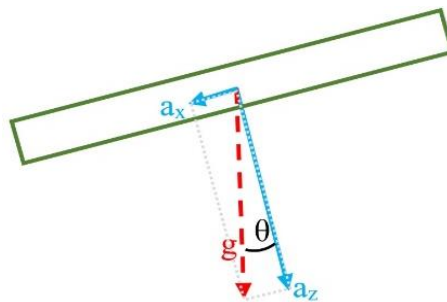


Figure 2. Accelerometer sensor vector

2.2. Using Kalman Filter to Filter Acceleration and Angle Velocity Value

Kalman filter in this study serves to reduce the disturbance due to lack of precision sensors to obtain optimal and stable results [11-18]. In this process is divided into covariance calculations (3 stages) and state calculations (2 stages). The calculation of covariance passes through three stages:

a. Calculate Kalman gain:

$$K_t = \frac{P_{t-1}}{P_{t-1} + R}$$

b. Calculate estimation:

$$\hat{x}_t = \hat{x}_{t-1} + K_t(z_t - \hat{x}_{t-1})$$

c. Calculate covariance error:

$$P_t = (1 - K_t)P_{t-1} + Q$$

The calculation of state passes through two stages:

a. Save last estimation value:

$$\hat{x}_{t-1} = \hat{x}_t$$

b. Save last covariance error value:

$$P_{t-1} = P_t$$

For the initial process before there is the last state value there will be an error, with the passage of time the filter process is repeated continuously so it will establish iteration then deviation value will be reduced to near reality value.

2.3. Acceleration and Angular Velocity Value Integrate

The output of the IMU sensor is the angular velocity and acceleration, to get speed value it must be done integrating process. The correlation between position, velocity and acceleration can be seen in Figure 3. There are various methods that can be used to integrate. Midpoint Riemann Sum is a single step method that is more accurate than the Euler method [19, 20]. This method estimates the derivative at the interval points, which are then summarized as shown in Figure 4. The Midpoint Riemann Sum method is the embryo of the integral, which integral can certainly be done by the approximation of the sum of the multiplicity of $f(x)$ multiplied by Δt . The smaller the value Δt results in more accurate readings [21, 22].

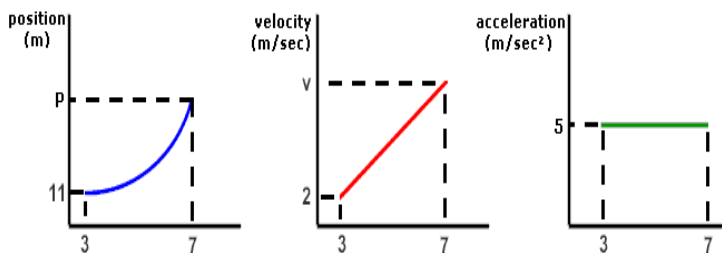


Figure 3. Correlation between acceleration, velocity, and position [19]

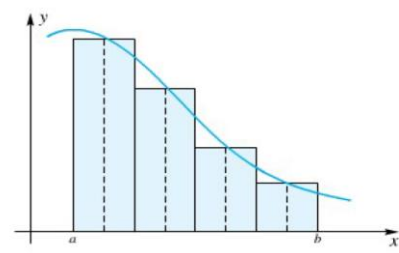


Figure 4. Integration using Midpoint Riemann Sum [20]

In the specification it has been determined that the speed rating will be updated a maximum of 1 meter once. Then it can be determined how the maximum time interval value for integration using Midpoint Riemann Sum method. The parameters in the specification are a maximum renewal range of 1 m and maximum speed is 140 km/h or can be written 38,888 m/sec. So it can be calculated for the maximum time interval as follows:

$$\Delta t_{\max} = \frac{S_{\text{update_max}}}{v_{\max}}$$

$$\Delta t_{\max} = \frac{1 \text{ m}}{38.88 \text{ m/s}}$$

$$\Delta t_{\max} = 0.0257 \text{ s}$$

$$\Delta t_{\max} = 25.7 \text{ ms}$$

with $S_{\text{update_max}}$ is the maximum distance to update the speed and v_{\max} is the maximum speed that the system can measure. The equation for the angular position can be written as follows :

$$\theta = \sum_{i=1}^n \frac{(\omega_i + \omega_{i+1})}{2} \Delta t$$

$$\theta_{(i+1)} = \theta_i + \frac{(\omega_i + \omega_{i+1})}{2} \Delta t$$

with $\Delta t < 25.7 \text{ ms}$. The equation for the velocity can be written as follows:

$$v = \sum_{i=1}^n \frac{(a_i + a_{i+1})}{2} \Delta t$$

$$v_{(i+1)} = v_i + \frac{(a_i + a_{i+1})}{2} \Delta t$$

with $\Delta t < 25.7 \text{ ms}$

2.4. Flowchart of System

Flowchart of the system used as reference of program making for IMU sensor value conversion until becoming speed value is shown in Figure 5. The flowchart consists of data retrieval process, digital filter process, angle position calculation, acceleration and speed value.

3. Results and Analysis

Testing is needed to analyze the performance of the system that has been made. The system has been made can be known performance by analyzing the output values in each sub-system.

3.1. Kalman Filter Test

Kalman filter here serves as a frequency damper due to noise that can be used to smooth the signal readings [23-25]. In this filter applied here has 2 control variables that are R and Q which have values between 0 to 1. Where R is the measurement noise covariant, while Q is the covariance of the process noise. The purpose of selecting the value of R and Q is as a parameter of determining the frequency attenuation, if attenuation is low then the signal still contains noise, if the damping is too high the noise decreases but the filter output readout is not too accurate. Based on Figure 6 can be seen that the output sensor still contains a lot of noise so impressed not too stable, therefore Kalman filter serves as a noise filter due to instability sensor output. Here is an unfiltered sensor output plot that has been through a fourier transformation so that it can be viewed in the frequency domain. From Figure 7 the output of the unfiltered sensor can be seen that the frequency distribution is between 10 Hz to 500 Hz.

Figures 8 (A), (B) and (C) and 9 (A), (B) and (C) show the sensor output plot using kalman filter that has been through a Fourier transformation so that it can be viewed in the frequency domain. In the data processing here there will be 2 variables in the test that is Q (0.1; 0.01; 0.001), shown in Figure 8 (A), (B) and (C), and R (0.0; 0.5; 1.0), shown in Figure 9 (A), (B) and (C). From this test can be concluded that the smaller value of Q then the frequency will be more muffled. From this test can be concluded that the greater value of R then the frequency will be more muffled.

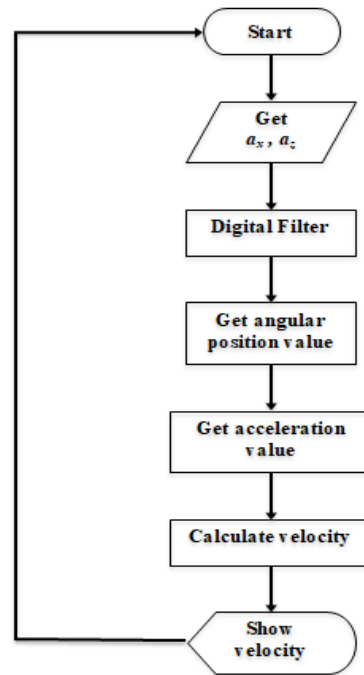


Figure 5. Flowchart of the system

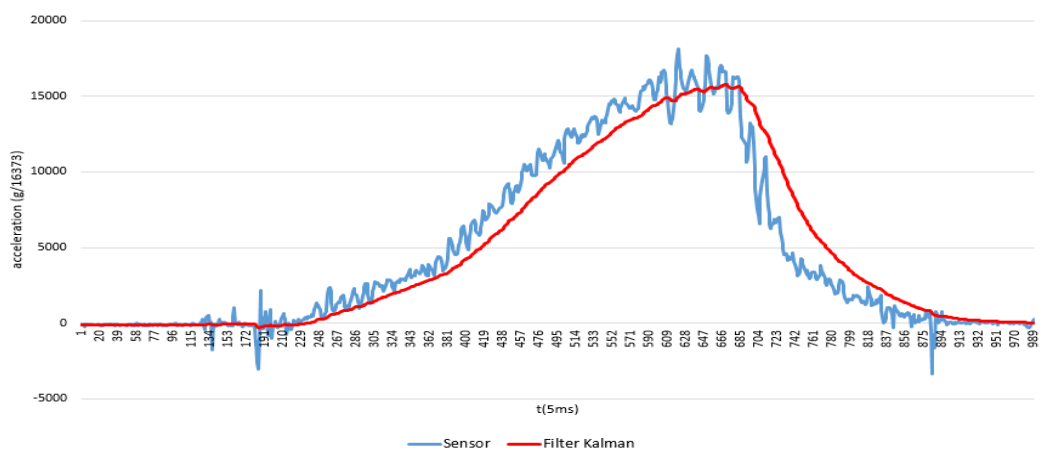


Figure 6. Corelation between output sensor and after pass the filter

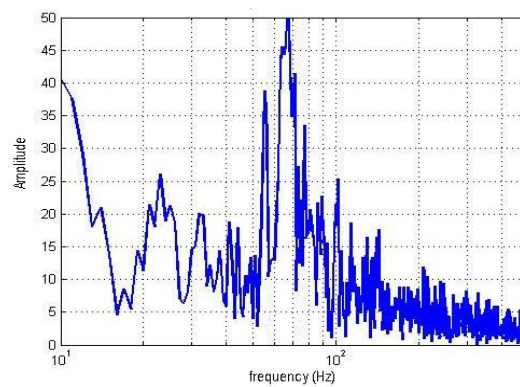


Figure 7. Sensor output frequency response without filter

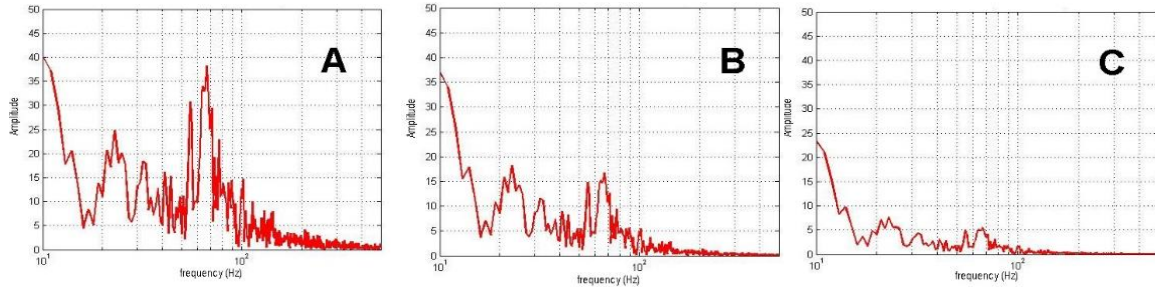


Figure 8. Output kalman filter with R value is 0,5 and Q independent variabel, (A) Q=0.1; (B) Q=0.01; (C) Q=0.001

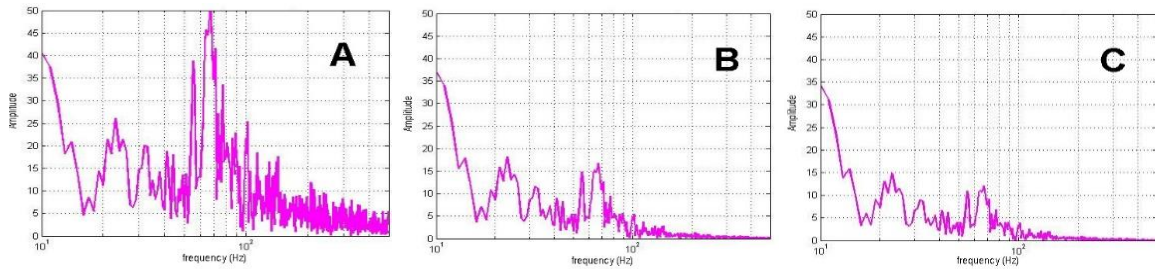


Figure 9. Output kalman filter with Q value is 0,01 and independent variabel R, (A) R = 0.0; (B) R = 0.5; (C) R = 1.0

3.2. Angular velocity integral

The angular velocity integral aims to obtain angular position values. In this integral processing use the midpoint Riemann sum method using AVR computation ie Atmega328 has been tested to perform data retrieval to bring up the angle position, the process takes $\pm 2,4$ ms as shown in Figure 10.

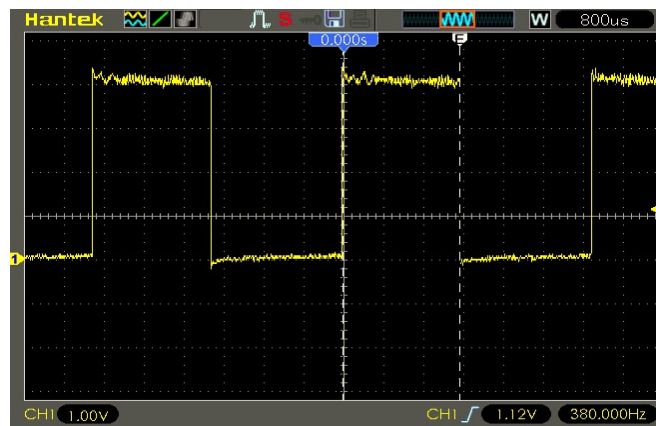


Figure 10. The time taken for data retrieval

Here is a comparison of test graph of integration value of angle velocity value to time with t value $t=5$ ms; 10 ms; 20 ms. From the graphs in Figures 11, 12 and 13, the integral result with midpoint rieman sum method, it can be seen that the smaller value of Δt generate integration resolution and data acquisition from the system will have a high accuracy value, but due to data acquisition processing until it appears angular position value take ± 2.4 ms then the smallest value for integration also has the smallest capability limit should be above

processing time. From the three graphs integral result with midpoint rieman sum method can be seen the smaller value of Δt generate integration resolution and data acquisition from the system will have a high accuracy value, but due to data acquisition processing until it appears angular position value take ± 2.4 ms then the smallest value for integration also has the smallest capability limit should be above processing time.

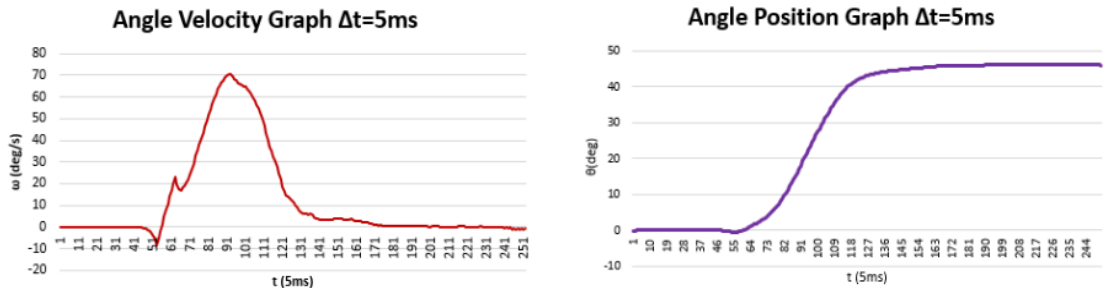


Figure 11. Angle velocity integration with $\Delta t=5ms$

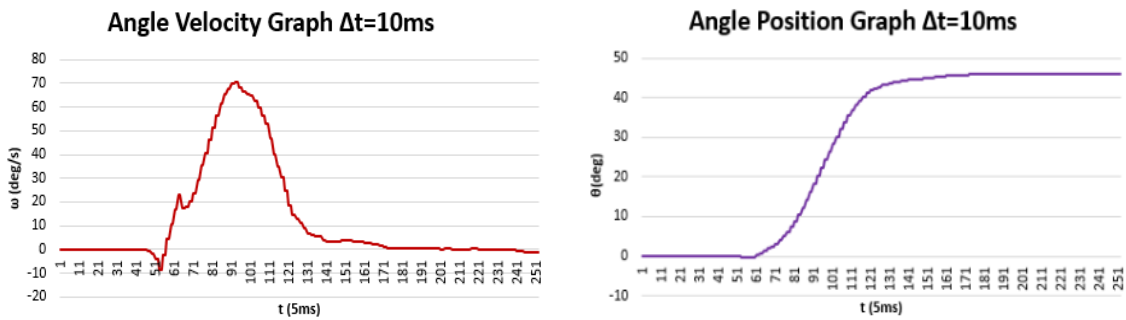


Figure 12. Angle velocity integration with $\Delta t=10ms$

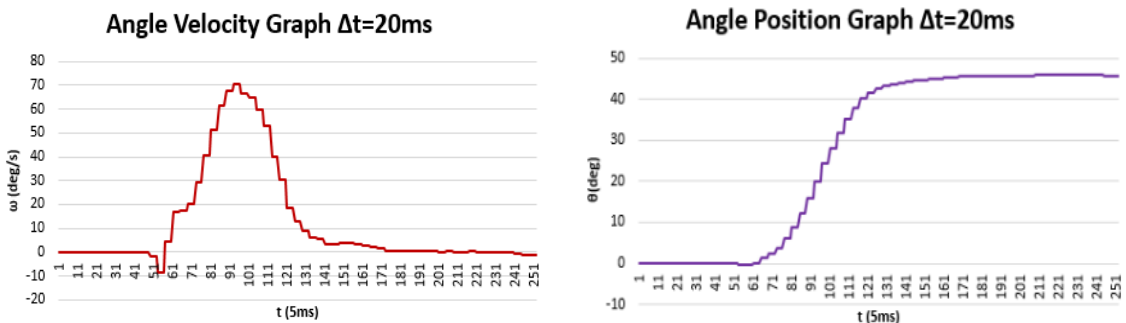


Figure 13. Angle velocity integration with $\Delta t=20ms$

3.3. Eliminate Value of Static Acceleration due to Earth Gravity

The dynamic acceleration readings aim to eliminate static acceleration readings caused by earth gravity so that the readable value is a pure acceleration parallel to the earth's surface. Here is a correlation graph between the x-axis acceleration sensor to the static acceleration value, which aims to accelerometer output values will display dynamic acceleration. According to the Figure 14 in a stationary state dynamic acceleration has a value of 0 m/s even though the IMU changes its angular position, the static acceleration captured by the x-axis sensor will be eliminated by dampening the value using angular readings on the sensor.

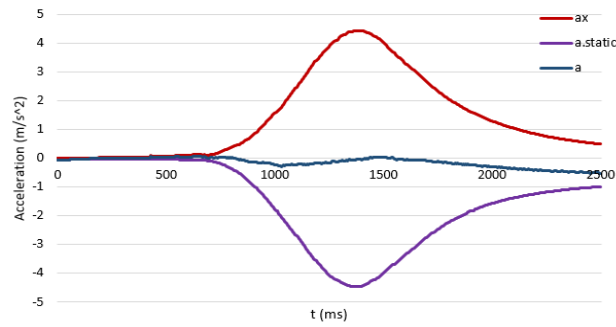


Figure 14. Comparison between a_x and static acceleration

3.4. RMSE in the State of Speed 0 m/s

The system has been made is not the ideal system it is necessary to test the error value of root mean square to know the error value in the state of speed 0 m/s. Tests take 500 data in the state of the stationary to obtain the identical treatment, in this test the independent variable is a θ value ($\theta=+45^\circ$; 0° ; -45°). Based on Figure 15, when the angle value of sensor is $+45^\circ$ obtained RMSE 0,8696 m/s and based on Figure 16 and Figure 17, when the angle value of sensor is 0° and -45° can be obtained the RMSE of 0,0393 m/s and 0.3030 m/s, respectively.

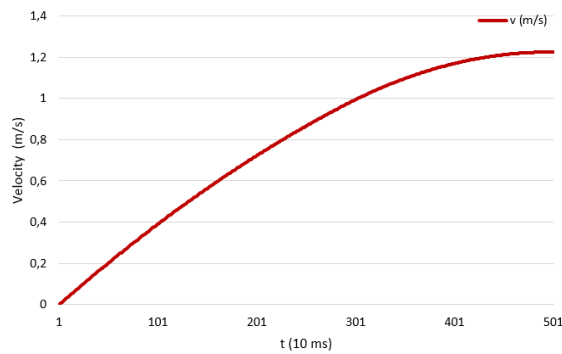


Figure 15. Value of 0 m/s captured by the sensor when the angle value is $+45^\circ$ in 5 seconds

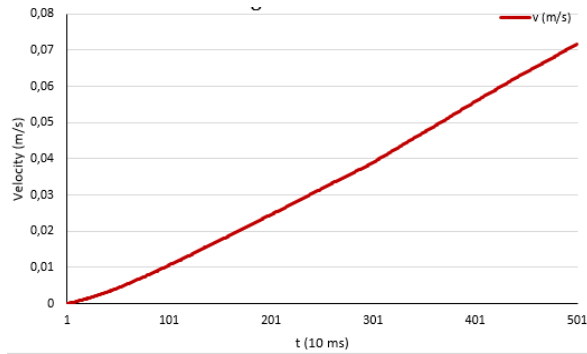


Figure 16. Value of 0 m/s captured by the sensor when the angle value is 0° in 5 seconds

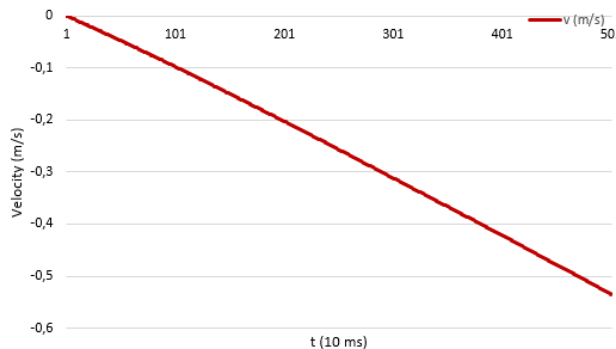


Figure 17. Value of 0 m/s captured by the sensor when the angle value is -45° in 5 seconds

4. Conclusion

After the research done by taking data and calculation of parameters and analysis, it can be concluded that static acceleration can be eliminated by a mathematical equation with

utilize gyroscope. Results obtained at the test of 0 m/s had an RMS error of 0.8696 m/s when elevation is $+45^\circ$; 0.0393 m/s when elevation is 0° ; and 0.3030 m/s when elevation is -45° .

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