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Rocket Velocity Estimation for RX-450 Launches Using Image Processing

Soleh Fajar Junjunan[1], Yuniarto Wimbo Nugroho[1], Bagus Hayatul Jihad[1]

[1]Research Center for Rocket Technology, BRIN, Indonesia

e-mail: sole003@brin.go.id

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Abstract

The RX-450 rocket, developed by the Rocket Technology Center BRIN, serves various purposes, from sounding to military applications. This study focuses on estimating rocket velocity during the launch phase. Using MATLAB for image processing and OpenRocket for simulation, we explore the potential of image processing for velocity estimation, providing a cost-effective alternative. Results show velocity estimations trailing those of OpenRocket, attributed to friction force and setup differences. The study emphasizes the importance of camera positioning for accuracy. Despite differences, image processing shows promise, warranting further refinement.

***Keywords**: Rocket velocity; Image processing; OpenRocket, Launch phase.*

1. Introduction

The RX-450 rocket, developed by the Rocket Technology Center BRIN, has the potential for development as both a sounding rocket and a military rocket. Notably, it stands as the largest rocket ever launched by the Rocket Technology Center BRIN, with a diameter of approximately 450 mm. The launch phase of this rocket is a crucial stage in its trajectory, serving as the initial step in determining its subsequent behavior and performance. Therefore, developing a method to estimate the rocket's velocity during this phase is important, as velocity is a critical parameter in rocket flight. Additionally, this study serves as an additional analysis of the flight performance of the RX-450 rocket conducted by Hakiki et al. (Hakiki et al., 2022).

In general, rocket velocity estimation relies on various methods, among which is the utilization of inertial sensors such as accelerometers, gyroscopes, or the Inertial Measurement Unit (IMU) or Inertial Navigation System (INS). Occasionally, these sensors are augmented with Global Navigation Satellite Systems (GNSS) satellite-based position sensors to enhance accuracy. Typically, INS is employed to ascertain the position, orientation, and velocity of an object relative to its initial state. However, one drawback of the inertial system is its limited accuracy over prolonged durations, primarily due to the necessity of double integration of acceleration to derive position. Furthermore, any errors in acceleration measurement are compounded through integration, leading to biases in estimated velocity and positional deviation (Berrabah & Baudoin, 2011).

Moreover, the Rocket Technology Center BRIN currently relies on Micro-Electro-Mechanical Systems (MEMS) Sensors, which exhibit inferior accuracy compared to laser-type sensors such as ring-laser gyroscopes. Although efforts have been made by the Rocket Technology Center BRIN team to integrate satellite-based navigation systems, such as the *Global Navigation Satellite System*, into their rockets, these systems have not adequately addressed the challenges associated with estimating rocket velocity. This limitation is compounded by regulations imposed by the Coordinating Committee for Multilateral Export Controls (COCOM), which restrict the use of certain devices.

Another method for determining the velocity of a rocket at launch involves utilizing the Doppler method. This entails measuring Doppler shifts in radio signals transmitted to or reflected from the rocket (Salinger, 1970). This method has also been applied to the RX-200 rocket belonging to BRIN's Rocket Technology Center with a transponder frequency design of 880 MHz. (Widada, 2012). On the other hand, the use of classic passive Doppler radar requires a fairly long integration time for the desired range when applied to estimate vehicle movement, especially limitations in detecting the velocity of targets experiencing acceleration. This is because the target movement model has been simplified when used to design the detector (Solatzaheh & Zaimbashi, 2018).

Several methods for estimating rocket velocity during the initial stage are available, but there is a lack of literature discussing image processing methods for estimating velocity during the launch stage. Several studies have explored the utilization of image processing techniques in rocket applications, yet their application in estimating launch velocity remains underexplored. For instance, researchers have employed image processing alongside a high-speed camera capable of capturing 12,000 frames per second to develop a high-speed motion analysis system for solid rocket motors. This system facilitates the examination of anomalies in propellant combustion during the launch phase (Liu, He, Li, Liu, & Chen, 2007).

On the other hand, other studies have explored the utilization of image processing techniques to describe how the attitude of sounding rockets, launch vehicles, or satellites can be estimated by analyzing Earth's horizon features in camera images(Braun & Barf, 2023). While image processing methods have been extensively applied to estimate the velocity of objects other than rockets, such as vehicles and various other entities(Doğan, Temiz, & Külür, 2010; Lu, Wang, & Song, 2020; Madasu & Hanmandlu, 2010), the obtained images are typically converted into binary form. Subsequently, the vehicle's velocity can be estimated by analyzing the differences between sequential frame numbers corresponding to the input images (Czapla, 2017). Hence, this study aims to explore image processing methods for velocity estimation during the launch stage, benefiting from their potential cost-effectiveness and the absence of high-cost equipment requirements.

2. Methodology

Our methodology comprises two main components: image processing and simulation using OpenRocket. Firstly, we utilize MATLAB for image processing. In parallel, we conduct simulations using OpenRocket to validate the accuracy of velocity estimations obtained through image processing. The methodology for both is explained in the following subsection.

2.1. Image Processing

Image processing encompasses a range of techniques employed to execute various operations on images with the aim of enhancing them or extracting specific information. It constitutes a subset of signal processing wherein the input is an image, and the output comprises either an enhanced image or characteristics associated with the original image. The proposed image processing algorithm is applied to videos or images captured during real rocket launches using uncalibrated cameras, with the aim of estimating the rocket's speed. One notable advantage of this method lies in its simplicity, cost-effectiveness, and satisfactory accuracy in determining the rocket's velocity.

The initial step of our methodology involves extracting frames from the video footage of the rocket flight experiment. In this context, the image processing technique is the filtration of frame images to isolate a specific target area, serving as a marker. At this early stage of our study, the process of automatically obtaining such a marker directly from the video exceeds our current capabilities. Consequently, we manually designate a marker on each frame by utilizing the blue color, as illustrated in Figure 2-1. This choice is intentional, considering that the red hues typically associated with fire emitted by the rocket and the green intensities common in tree foliage could complicate the marker selection process. The limitations of this approach highlight the potential for future research to explore alternative marker identification methods, such as utilizing the exhaust plume as a target marker.

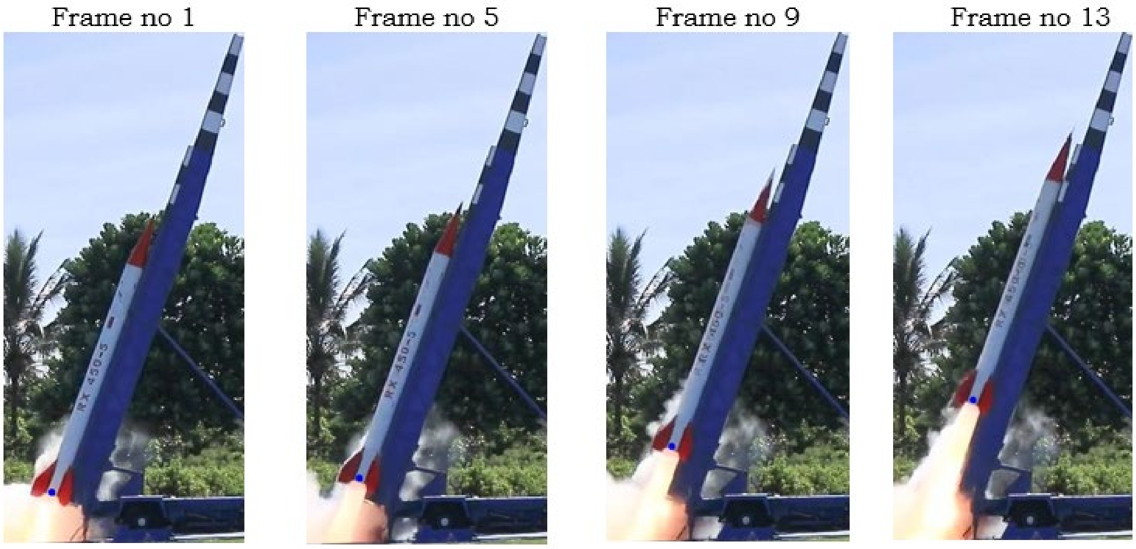


Figure 2-1: Image Frame of RX-450 Launch on the Launching Rod with the Blue Marker.

The next procedure of our method is explained by the following:

- The loop iterates over a series of image frames of the rocket launch.
- For each frame, it reads the image file, extracts the red, green, and blue channels, and stores them in separate matrices.
- It then applies thresholding conditions to filter out unwanted pixels in the image. If a pixel's intensity in the red or green channel is greater than 50, or if its intensity in the blue channel is less than 200, it sets all three channels to zero, effectively removing those pixels from consideration.
- After filtering, the code converts the image to grayscale, fills any holes in the image, and extracts the largest connected component.
- It labels each connected component using the bwlabel function.
- The centroid for the filtered marker in each frame is calculated and stored.
- The centroids are then converted from pixel units to physical units (millimeters) using a conversion factor of 22.405 mm/pixel.
- Finally, the code calculates the velocity.

The conversion factor from pixel units to physical units is calculated by the comparison of actual dimensions and the number of pixels. The results of the filtered image, which accumulated in one figure, are shown in Figure 2-2. Velocity can be calculated by Eq.2-1, 2-2 and 2-3.

$$V = \sqrt{V_x^2 + V_y^2} \tag{2-1}$$

$$V_x = \frac{x(i) - x(i-1)}{dt} \tag{2-2}$$

$$V_y = \frac{y(i) - y(i-1)}{dt} \tag{2-3}$$

Where dt is calculated from the camera frame per second.

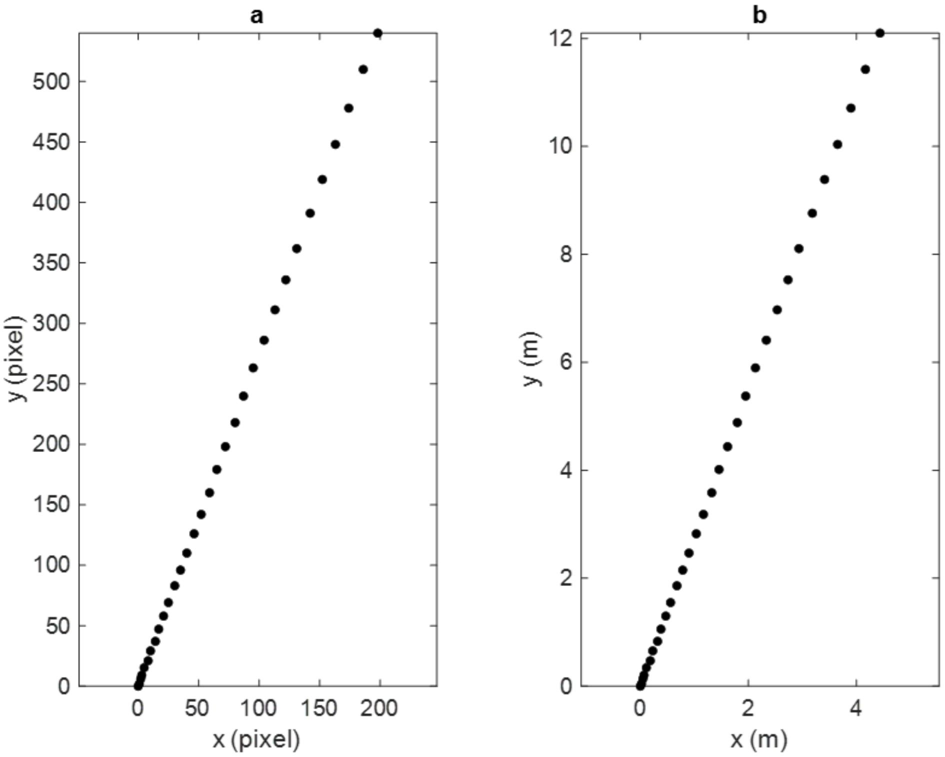


Figure 2-2: Filtered Frame Collected in One Figure a) in the pixel unit and b) in the physical unit.

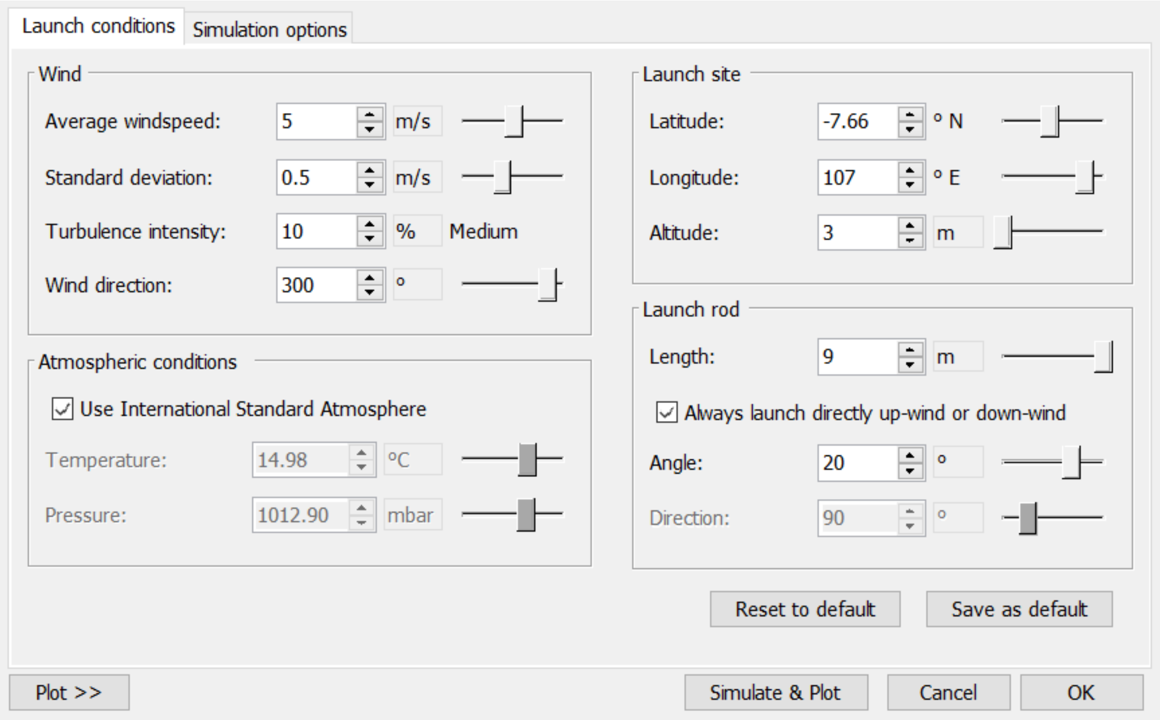
2.2. Simulation by OpenRocket

OpenRocket is an open-source software application that allows users to design and simulate rocket launches. It provides a platform for designing various aspects of rocketry, including rocket configurations, propulsion systems, and flight simulations. OpenRocket is widely used by hobbyists, students, and professionals in the field of aerospace engineering for designing and analyzing rocket systems (Brown et al., 2019; Rohini et al., 2022).

RX-450 model is built in the OpenRocket. In our model, we only use a general shape configuration of the rocket, and we neglect the detailed design, such as screws, connectors, payload, etc. We adjust the weight and CG position by positioning a virtual balance inside the tube in order to have a similar weight and CG position to the actual rocket. The model is shown in Figure 2-3.

Figure 2-3: RX-450 Model in OpenRocket.

For the input of rocket propulsion, such as thrust profile, provided from the rocket static test, more information about the propulsion analysis of RX-450 can be found in the literature (Abyan et al., 2022; Al Farizi et al., 2018). The simulation parameter is shown in Figure 2-4.



Wind
Average windspeed: 5 m/s
Standard deviation: 0.5 m/s
Turbulence intensity: 10 % Medium
Wind direction: 300 °

Atmospheric conditions
☑ Use International Standard Atmosphere
Temperature: 14.98 °C
Pressure: 1012.90 mbar

Launch site
Latitude: -7.66 ° N
Longitude: 107 ° E
Altitude: 3 m

Launch rod
Length: 9 m
☑ Always launch directly up-wind or down-wind
Angle: 20 °
Direction: 90 °

Figure 2-4: Input Setting OpenRocket.

In the context of the wind condition, it varies according to the height. Because our concern is in the launch phase, we use and assume that the wind speed is constant during the rocket flight, with an average windspeed of about 5 m/s and 300° of wind direction. We assume the wind condition's standard deviation and turbulence intensity are 0.5 m/s and 10%. The rail for the launch rod is about 9 m, with the total length of the launch rod is about 12 m. The rocket is launched with an elevation angle of about 70°. In the OpenRocket, the elevation angle is from the vertical, that's why in the input 20°. The launch site is located in Pameungpeuk Garut with the coordinate around for latitude -7.66 °N and longitude 107.69 °E, although in OpenRocket, its automatically rounded to 107 °E. The location of the launch site can be found on Google Maps, as shown in Figure 2-5.

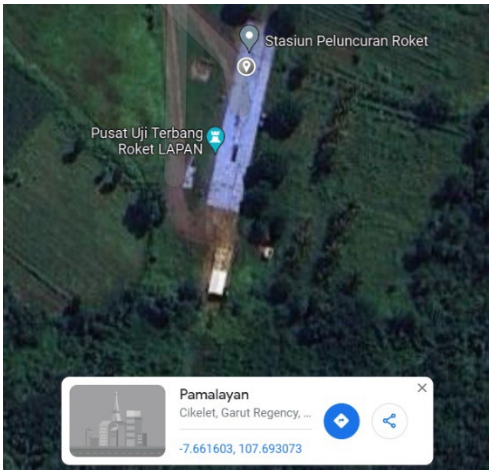


Figure 2-5: Launch Site Location.

Figure 2-6 shows the rocket's altitude and flight time to verify the simulation results. The results show the apogee is almost 30 KM, with a flight time of about 166 s. Although the simulation included some assumptions that are explained, these results are consistent and close to the results by GPS (see ref Hakiki et al., 2022 for the comparison). Therefore, we can compare the results with the image processing method. We re-simulate the RX-

450 flight test because the literature (Hakiki et al., 2022) does not give a detailed calculation with the launch rod.

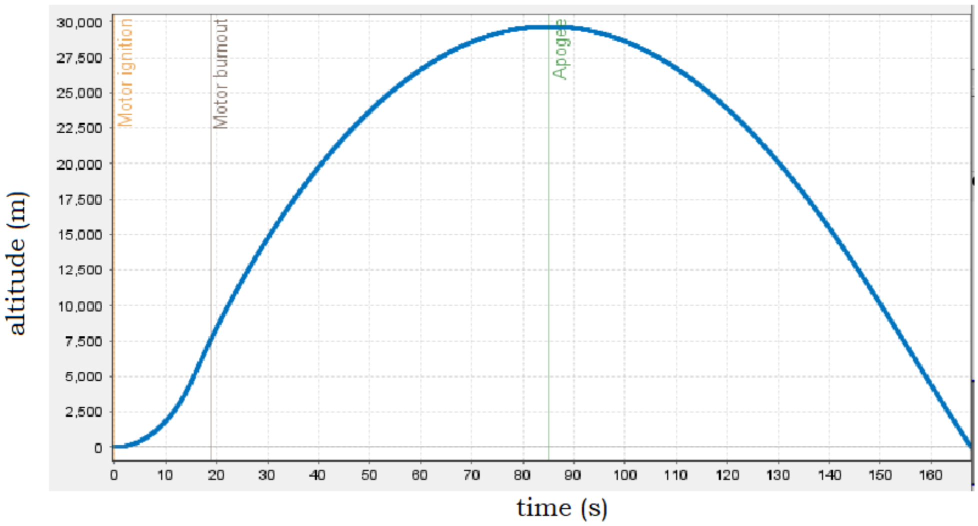


Figure 2-6: Altitude with the Flight time obtained by OpenRocket.

3. Result and Analysis

The velocity estimation calculated by OpenRocket simulation and image processing method are presented in Figure 3-1.

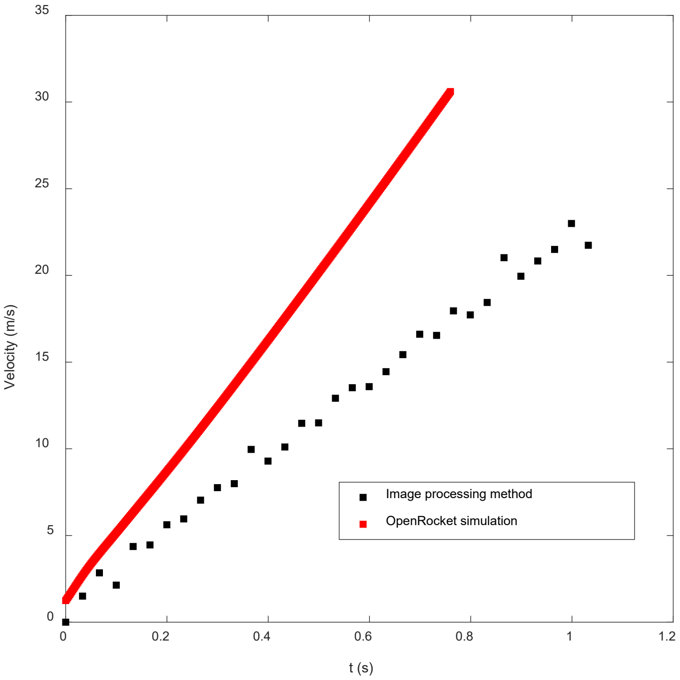


Figure 3-1: Rocket Velocity on the Launching Rod.

Figure 3-1 shows that velocity estimation by the image processing method is consistently below the OpenRocket simulation. In the beginning, the difference is relatively small, then the difference increases with the increase of time. Therefore, in the simulation, the rocket travels in the launching rod for about 0.76 s, while for the image processing, representing the experiment, it is about 1.03 s. In the simulation by OpenRocket, the velocity while the rocket is still in the launching rod can reach up to about 30.5 m/s, while by the image processing method is about 23 m/s. This can be because of various factors. In our opinion, it may be because of the friction force of the rocket with the launching rod.

These results have practical implications for the launch of the rocket. The significant friction force leads to reduced velocity, which is also significant when it comes out of the launching rod. This will suddenly change the rocket's pitch angle and may affect the rocket's trajectory. To overcome this problem, we increase thrust to thrust-to-weight ratio, but then it will increase the Mach number of the rocket when it flies and may resulting another problem such as stability, structure integrity, or too high G force, which can affect at least the electronic equipment. Or, we can extend the launching rod, but it may not be effective if the cause of the significant reduce in velocity is significant friction force. Another solution can be re-designing in sliding -block in order to have a smaller friction coefficient.

Nevertheless, it doesn't mean that this image processing method is better and more accurate. Although the time required to travel is accurate, the orientation and camera position will have an effect on the accuracy of the velocity estimation. While it may also be interesting to complement another method in the future, the improvement of the proper camera position, calibration, and orientation needs to be planned so we can convert from the pixel to the physical value with more correct. The use of stereo cameras can also be planned to increase accuracy in estimating velocity on rockets. It has been proven that systems with stereo cameras have been proven to be quite accurate in detecting vehicle velocity(Llorca et al., 2016; Najman & Zemcik, 2022).

4. Conclusions

This study has demonstrated the potential of image processing methods for estimating rocket velocity during the launch phase, offering a cost-effective alternative method. The results show a similar trend to simulations by OpenRocket. While there are differences in velocity estimates between the two methods, primarily attributed to setup variations and friction forces, the image processing approach has the potential to be developed more. However, it is crucial to acknowledge that the accuracy of velocity estimation may be influenced by factors such as camera orientation, calibration, number of cameras, and position. Future research endeavors should prioritize refining these aspects and developing improved filter methods to enhance the accuracy and reliability of velocity estimation through image processing.

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Contributorship Statement

All of the authors are the main contributors.

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