Sensor Fusion – Based Localization for ASV with Linear Regression Optimization

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ABSTRACT

ASV (Autonomous Surface Vehicle) is one of popular innovations in the maritime field that is widely used for various missions on the water surface. The ASV itself has the ability to operate automatically without human intervention. Therefore, ASV requires an accurate and reliable localization system. This research focuses on developing an ASV localization system using waterflow sensors optimized through linear regression and integrated with orientation data from an IMU sensor through sensor fusion to obtain global coordinate position estimation. The experiments conducted showed a significant improvement in accuracy after optimization, with the Root Mean Square Error (RMSE) of the waterflow sensor data decreasing from 161.65 meters to 0.28 meters. Moreover, the yaw data reading by IMU achieved accuracy with RMSE 1.54 degrees. The localization system in the final test achieved RMSE values of 0.07 meters for the X-axis, 0.14 meters for the Y-axis, and 1.9 degrees for yaw during the ASV global positioning experiment. In addition, a GUI (Graphical User Interface) was developed for visualization with average communication latency of 113.6 milliseconds. This localization system is a promising solution in stable water condition.

I. INTRODUCTION

ASV (Autonomous Surface Vehicle) is one of the technological innovations in the maritime field that is growing rapidly in the last few decades [1]. ASV is a vessel designed to be able to carry out various missions on the water surface automatically or without direct human intervention [2] [3]. Compared to conventional marine vessels, ASVs have the ability to autonomously perform certain missions such as data collection, maritime environment observation, defense duties, rescue tasks [4] [5], and involvement in maritime educative competition.

International Roboboat Competition (IRC) [6] and *Kontes Kapal Cepat Tak Berawak Nasional* (KKCTBN) [7] are educational competitions that use autonomous ship as their main platform. These competitions are often held in calm waters such as ponds and lakes near urban areas. The competitions also give participants missions to complete.

Several studies have been conducted to ensure the ASV can fulfill its missions well. One of them is research on omni-directional movement that allows the ship to move in any direction by utilizing the proper thruster configuration [8]. However, relying on the omni-directional movement system alone is not sufficient. The ASV also requires a reliable localization system.

Localization system allows an autonomous robot or vehicle to know its actual position [9]. A localization system involves establishing a correspondence between a local coordinate system and global coordinate system [10]. An effective localization system must be able to provide accurate and real – time data [11], considering ASV significantly relies on position and orientation data to be able to plan for the next actions. In its implementation the localization system uses various methods to improve the accuracy and reliability of the generated data.

The Global Positioning System (GPS) is one of the most widely used positioning technologies due to its global coverage and ease of implementation. However, there are certain operational characteristic that can pose challenges in specific applications. GPS signals can degrade in environments with physical obstructions such as pools, tunnels, or densely populated urban coastal areas due to multipath effects [12]. GPS is also vulnerable to jamming and spoofing [13]. Additionally, there is no direct orientation information.

In addition to GPS, there is also an inertial – only method that relies on data from IMU (Inertial Measurement Unit). This method offers advantages such as high refresh rates and low dependence on internal infrastructure. However, this method is susceptible to cumulative drift, which is the accumulation of errors over time due to continuous integration processes [14].

To address these limitations, this study proposes an odometry – based localization system using waterflow sensor [15] [16] integrated with yaw orientation data from IMU. In the proposed method, the waterflow sensor functions similarly to wheel encoders in the ground robots [17] [18], providing an estimate of distance travelled relative to an initial position. The risk of degradation, jamming, and spoofing can be reduced because the odometry method obtains data directly from the installed movement sensor [19], not from GPS signals. In addition, the use of waterflow sensors can reduce cumulative drift from inertial – only methods because in the proposed localization system IMU only needs to provide yaw data (heading). which is needed to convert local coordinates into global coordinates. This fusion is performed through two – dimensional transformation using rotation matrices [20].

To improve the accuracy of the waterflow sensor, an optimization process was carried out using linear regression [21]. Linear regression was used to convert waterflow pulse data into accurate distance estimates and combined with IMU orientation data to produce global positions. Although linear regression is not a new approach in sensor optimization, its novelty in this study lies in its implementation in producing accurate distance estimates on the ASV platform. Linear regression was chosen because it is simpler, easier to implement, and has provided adequate optimization results.

In addition, this localization system is equipped with GUI (Graphical User Interface). This GUI is designed to monitor and visualize the localization system in real-time. This feature enables further analysis of the localization system's performance.

By utilizing the advantages of each sensor, the integration between the waterflow sensor and IMU through sensor fusion approach is expected to provide an accurate localization capability. Especially in stable and calm water where maritime competitions are often held without GPS signals. This study aims to evaluate the impact of linear regression optimization on the accuracy of waterflow sensor measurements, checking if the two – dimensional transformation can transform local coordinate to global coordinate, and demonstrating that a simple, real – rime, and lightweight localization can be applied to an ASV platform.

II. METHOD

In this section, the research steps to achieve the goal of the ASV localization system are described. The research methods include mechanical configuration, system block diagram, localization, GUI (Graphical User Interface), and evaluation.

A. Mechanical Configuration.

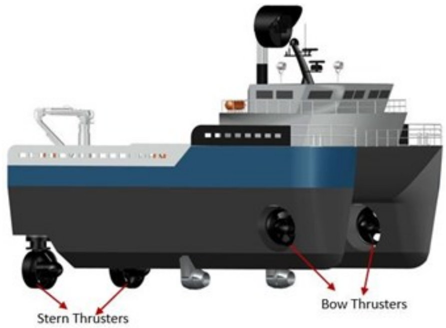

Figure 1. Autonomous Surface Vehicle (ASV) Design

In this research, we use a catamaran type ASV (Autonomous Surface Vehicle). Catamaran is a type of ship with two hulls connected by a bridging structure [22]. From Figure 1, it can be seen that the ASV has four thrusters where two thrusters are located behind the hulls (stern thrusters) and the other two are located in front of the hulls (bow thrusters).

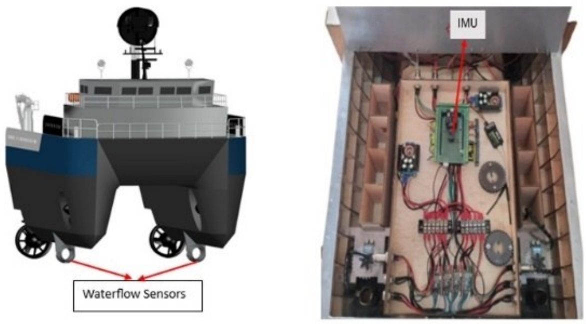

Figure 2. Waterflow Sensors and IMU Placement

There are two types of sensors used in this research, namely waterflow and IMU (Inertial Measurement Unit) sensors with the placement configuration shown in Figure 2. The waterflow sensors are installed at the middle and bottom of both hulls. Meanwhile, the IMU sensor is located inside the ship's deck, at the central of the ship. This IMU position serves as reference for the ASV orientation pivot point to support the localization system.

B. System Block Diagram.

The system block diagram used in this research is shown in this figure below.

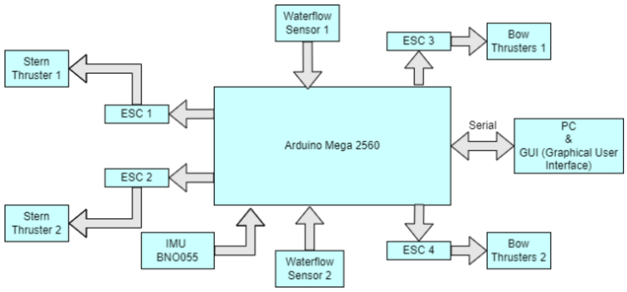

Figure 3. Localization System Block Diagram

From Figure 3, it can be seen that in ASV localization system, the microcontroller used is Arduino Mega 2560. Then, there are four thrusters (two stern thrusters and two bow thrusters) that act as actuators of the ASV. Not to forget, the drive control for the thrusters used on the localization system is ESC (Electronic Speed Controller). In addition, there are two YF-B6 waterflow sensors used to obtain distance data and one IMU BNO055 sensor to obtain ASV orientation data.

Arduino Mega 2560 as the central control has the role of controlling the speed and direction of the rotation of the four thrusters through ESC. Besides that, Arduino Mega 2560 also plays a role to receive data from the YF-B6 waterflow sensors and BNO055 IMU sensor and pass it to the PC (Personal Computer) via serial data communication to be visualized through the GUI (Graphical User Interface).

C. Localization.

The method used in this localization system is odometry method. Odometry method calculates the change in relative position coordinates over time from the movement of the actuator [23]. In the ASV, the sensor used as input for the odometry method is waterflow sensor. Waterflow sensor is a sensor that can detect the flow of water through the rotor and also equipped with hall-effect that can generate pulses or values [24]. Sensor waterflow is used to obtain actual distance data from the ASV in meters. Therefore, the output values of waterflow sensor need to be optimized.

The method used for the optimization is linear regression method. Linear regression method is a statistic method that aims to find a linear relationship between the independent variables (x), which are the waterflow sensors' raw values and the dependent variables (y), which are the actual distances in meters. To optimize the waterflow sensors with linear regression, several steps and calculations are required.

First, sample data are collected by running the ASV along a straight path as far as the actual distance (y), measured manually using a measuring tape to serve as the ground truth reference. The values from both waterflow sensors (left waterflow sensor and right waterflow sensor) are averaged using the equation 1.

$$\bar{x} = \frac{x_a + x_b}{2} \tag{1}$$

Where $\bar{x}$ is the average value of both waterflow sensors. while x_a and x_b represent the value of each waterflow sensor. This process is repeated n times with different actual distances (y). Each iteration will get a set of $\bar{x}$ and y data.

The next step is to calculate the coefficient (m) and constant (c) using equations 2 and 3.

$$m = \frac{n\sum(\bar{x}_i y_i) - \sum\bar{x}_i \sum y_i}{n\sum(\bar{x}_i^2) - (\sum\bar{x}_i)^2} \tag{2}$$

$$c = \frac{\sum y_i - m\sum x_i}{n} \tag{3}$$

Where m is the coefficient, c is the constant, n refers to amount of data, $\bar{x}_i$ is the mean value of waterflow at i-th measurement, and y_i represents the actual distance for i-th measurement. After obtaining the values of coefficient and constant, the linear relationship between the waterflow sensor and the actual distance can be represented by equation 4.

$$y_{pred} = m\bar{x} + c \tag{4}$$

Where y_{pred} represents the estimated actual distance in meter, m represents the coefficient or the rate of change in y_{pred} over time. Then, $\bar{x}$ is the average value of two waterflow sensors, and c is the constant value when $\bar{x}$ equals zero.

After the optimization process is done, the y_{pred} value will be used as input for the localization system. However, y_{pred} is still in local coordinate system. In order for the localization system to determine the position of the ASV in global coordinate system, the estimated actual distance (y_{pred}) needs to be combined with the orientation data obtained by the IMU BNO055 sensor.

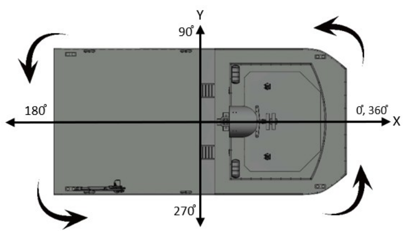

Figure 4. ASV Yaw Orientation

The process of combining data is done using the sensor fusion method. Sensor fusion is an approach that integrates data from multiple sensors to improve system accuracy and reliability. In this case, the IMU orientation (yaw) value is used to determine the facing direction with the configuration corresponding to Figure 4, while the distance data from waterflow sensor is used to calculate the position change of the ASV.

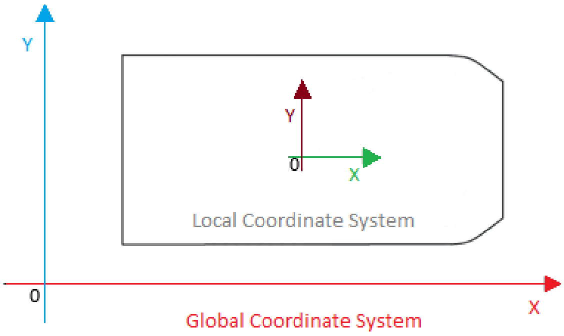

Figure 5. Initial Position Reference

It can be seen from Figure 5 that the difference between local coordinate system and global coordinate is on the ASV itself, while the origin point of global coordinate system is in surrounding environment when the ASV first moves. This causes the local coordinate system to rotate according to the movement of the ASV and the global coordinate remains constant. To know the global position of the ASV, the local position of ASV needs to be converted using two-dimensional rotation formula according to equation 5.

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} \begin{bmatrix} y_{pred} \end{bmatrix} \quad (5)$$

Where θ is yaw orientation. X and Y are the estimation values of ASV actual global position. And y_{pred} is the estimated actual distance in meter which is generated by waterflow sensors.

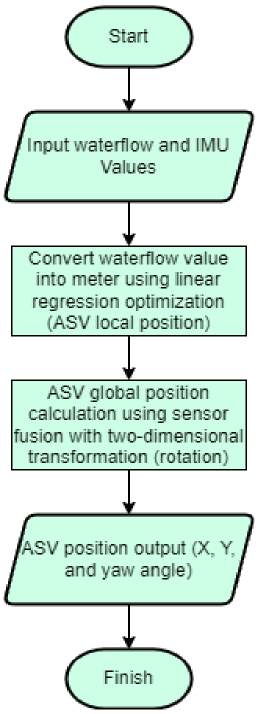

Figure 6. Flowchart of ASV Localization System

Figure 6 shows the flowchart of the offered localization system. This localization system focuses on the position of the ASV in X and Y axes. In addition, there is also the orientation (yaw) value of the IMU which is used to obtain the position of the ASV in global coordinate system.

With this approach, the localization system is designed to remain simple yet capable of producing accurate position estimates. This approach takes into account the limitations of the embedded system hardware used, as well as its need for implementation in a stable competition environment.

D. Graphical User Interface (GUI).

Graphical User Interface (GUI) is an interface that lets people to engage and communicate with the system or device [25] [26]. The GUI is designed to facilitate monitoring and visualization of data obtained from the ASV localization system.

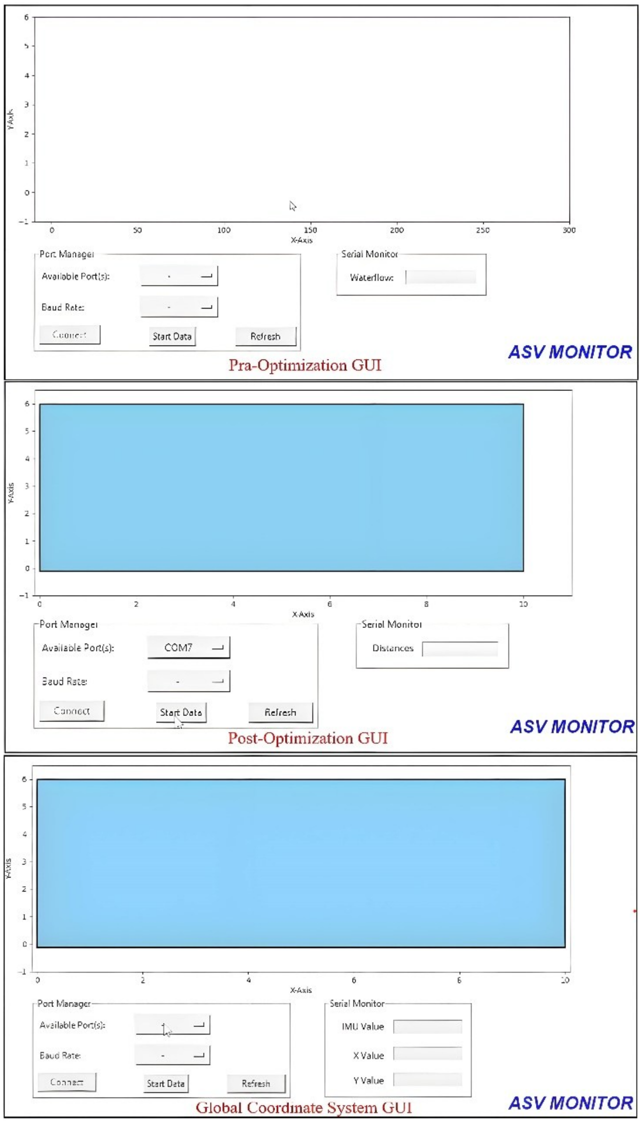

Figure 7. Graphical User Interface

This GUI is developed using python programming language by utilizing libraries such as Tkinter for interface and Matplotlib for data visualization. The GUI receives data from waterflow via serial communication using USB Type A to Type B cable.

From Figure 7, it can be seen there are three GUI used in this localization system.

1) *Pre-Optimization GUI:* This GUI is used to display the value of waterflow sensor in real time before optimization.

2) *Post-Optimization GUI:* The post-optimization GUI is useful for visualizing the value of the waterflow sensor after the optimization is performed. The data displayed already reflects the actual distance value of the ASV.

3) *Global Positioning GUI:* The global positioning GUI visualizes the global positioning of the ASV in the actual environment after sensor fusion. The ASV position is displayed in X, Y, and yaw angle outputs.

E. Evaluation.

To test the performance of the proposed localization system, two evaluations were conducted, namely:

1) *Root Mean Squared Error (RMSE):* RMSE is used to measure the average square difference between the position estimate value by the system and the actual value (ground truth) using the formula in equation 6.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (6)$$

Where y_i represents the actual position of the ground truth or actual position, $\hat{y}_i$ represents the estimated position by the localization system, and n is the amount of data. The smaller the RMSE value, the more accurate the proposed localization is.

2) *Latency Evaluation:* To assess the performance of data communication at proposed localization system, a test was conducted by recording the time when data was sent from Arduino Mega 2560 and when it was received by GUI in milliseconds. This time difference was used to calculate communication latency, while the interval between data was analyzed to determine the stability of the transmission and reception frequency. This test aimed to ensure that the localization process was real-time and stable.

III. RESULT AND DISCUSSION

This section will discuss the results and analysis obtained from the experiments conducted. The results will be presented in the form of figures and the tables to facilitate understanding. The discussion section highlights several topics such as IMU accuracy, waterflow optimization using linear regression, global position obtained using sensor fusion, latency experiment and limitations and future work. These points are crucial to understand the accuracy and reliability of the proposed localization system.

A. IMU BNO055 Experiment.

BNO055 IMU testing was conducted to determine the yaw direction of the ASV. The data will be integrated with the waterflow sensor using a sensor fusion approach for global positioning.

Figure 8. IMU BNO055 Experiment

From Figure 8, it can be seen that the test is performed by rotating the ASV at a certain angle. The output value of the IMU BNO055 sensor will be observed and recorded. This test is conducted on land using a backless swivel chair as an assistive device.

In the yaw test on the BNO055 IMU as listed in Table 1, the ASV was rotated to angles of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. So, the Root Mean Square Error (RMSE) value obtained in the test is 1.54 degrees.

TABLE I
IMU BNO055 YAW EXPERIMENT

Target Orientation (°)	**IMU BNO055 Orientation (°)**	**Error (°)**
0	0	0
45	46	1
90	87	3
135	133	2
180	178	2
225	225	0
270	269	1
315	315	0
RMSE		1.54

B. Waterflow Optimization.

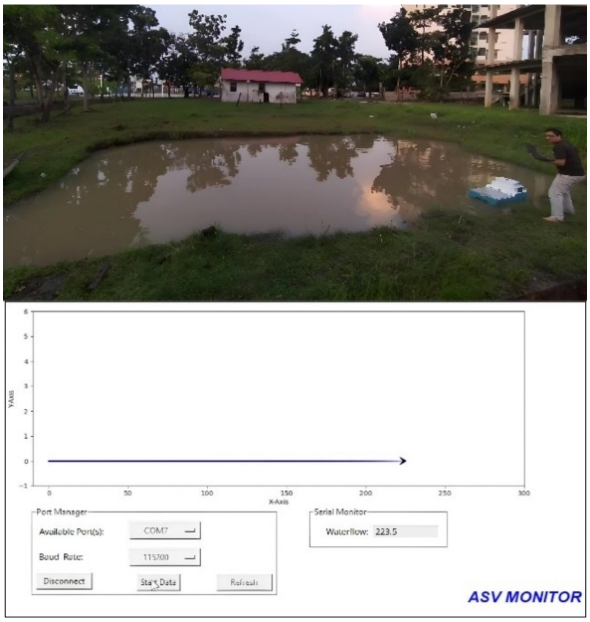

Figure 9. Waterflow Data Acquisition

From Figure 9, it can be seen that waterflow optimization is carried out with the aim of converting the waterflow value into the actual distance. The first thing that needs to be done is to acquire the waterflow sensor data against ground truth. Ground truth was obtained through manual measurements using a measuring tape with reference distances set at 0, 2, 4, 6, 8, and 10 meters.

Table 2 presents the unoptimized (raw) waterflow sensor data at ground truth points. The RMSE value obtained is 161,65 meters, which means that the waterflow's raw data is not accurate. To do the optimization, it was necessary to find the coefficient and constant values using equation (2) and (3).

TABLE II
WATERFLOW SENSOR DATA BEFORE OPTIMIZATION

No	Distance in Meter (y)	Waterflow Values ($\bar{x}$)	$\bar{x}$. y	$\bar{x}$^2	Error (m)
1	0	0	0	0	0
2	2	40	80	1,600	38
3	4	95	380	9,025	91
4	6	160	960	25,600	154
5	8	220	1,760	48,400	212
6	10	290	2,900	84,100	280
Total	30	805	6,080	168,725	775
RMSE					161.65

Coefficient:

$$m = \frac{n\sum(\bar{x}_i y_i) - \sum \bar{x}_i \sum y_i}{n\sum(\bar{x}_i^2) - (\sum \bar{x}_i)^2}$$

$$m = \frac{6(6{,}080)-(805)(30)}{6(168{,}725)-(805)^2} = \frac{36{,}480-24{,}150}{1{,}012{,}350-648{,}025} \approx 0.0338$$

Constant:

$$c = \frac{\sum y_i - m\sum x_i}{n}$$

$$c = \frac{30-(0.0338)(805)}{6} = \frac{30-27.243}{6} \approx 0.4593$$

Linear regression equation:

$$y_{pred} = 0.0338\bar{x} + 0.4593$$

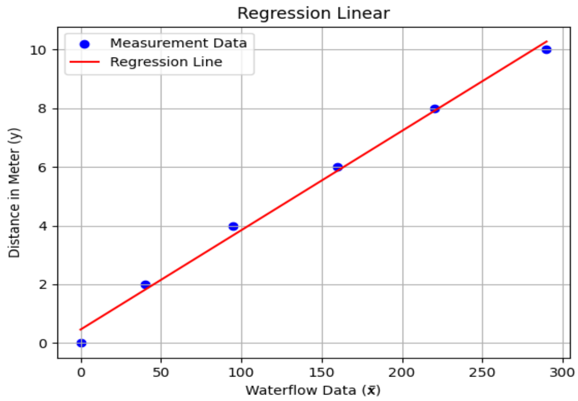

Figure 10. Linear Regression Optimization Chart

Based on the calculation made, the linear regression equation $y_{pred} = 0.0338\bar{x} + 0.4593$ is used for the waterflow optimization. When plotted, there will be a sloping line connecting the six data results obtained linearly, as shown in Figure 10. The last step is testing the optimized waterflow sensor.

Figure 11. Waterflow Optimization Experiment

After obtaining the linear regression equation, the next step is to conduct additional testing to ensure that the model that has been created is accurate, as shown in Figure 11. Based on the Table 3, the RMSE value of waterflow data before optimization was 161.65 meters dropped significantly to 0.28 meters, showing a significant improvement in distance measurement accuracy.

TABLE III
WATERFLOW SENSOR DATA AFTER OPTIMIZATION

No	Distance in Meter (y)	Optimized Waterflow (y_{pred})	Error (m)
1	0	0.46	0.46
2	2	1.81	0.19
3	4	3.67	0.33
4	6	5.87	0.13
5	8	7.90	0.10
6	10	10.27	0.27
RMSE			0.28

C. ASV Global Position Experiment.

The position in the global coordinate system is obtained by integrating the yaw data from the IMU BNO055 sensor with the distance data from the waterflow sensor using two-dimensional rotation. This test was conducted in a pool with calm water, without wind disturbances or adverse weather. The ASV will be placed at the initial reference point (0, 0) with X and Y axis setting as shown in Figure 12.

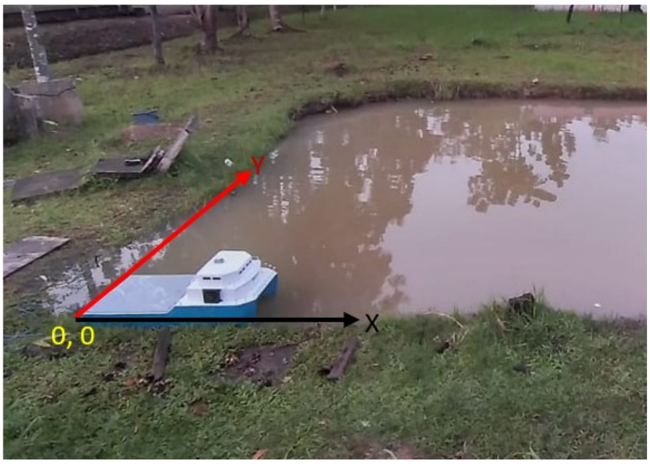

Figure 12. Initial Reference Point

In this experiment, the ASV begins at the initial position of (0, 0). The first action taken is a leftward rotation of 65 degrees relative to its starting orientation. Once the rotation is completed, the ASV moves forward in a straight path aligned with its new heading. This forward movement continues until the ASV arrives at the destination point located at coordinates (3, 6) meters. This sequence movement is shown in Figure 13, which illustrates the rotation and translation of the ASV in the global coordinate system.

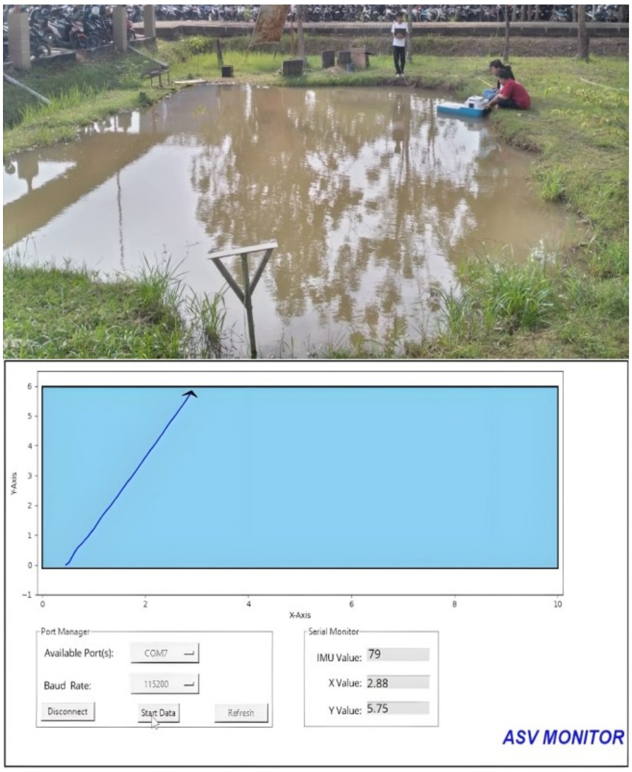

Figure 13. Global Positioning Experiment

From the experiment data listed in Table 4, the RMSE value obtained from five tests is 0.07 meters in the X-axis and 0.14 meters in Y-axis. Based on the experiment, the ASV localization system with the waterflow and IMU sensor has been proven to be accurate with RMSE value less than one meter.

TABLE IV
ASV GLOBAL POSITION EXPERIMENT

No	Destination			Global Position			Error		
	X (m)	Y (m)	Yaw (°)	X (m)	Y (m)	Yaw (°)	X (m)	Y (m)	Yaw (°)
1	3.00	6.00	65	3.00	5.90	65	0	0.1	0
2	3.00	6.00	65	2.99	5.85	64	0.01	0.15	1
3	3.00	6.00	65	2.88	5.75	67	0.12	0.25	2
4	3.00	6.00	65	3.09	6.06	68	0.09	0.06	3
5	3.00	6.00	65	3.01	5.92	67	0.01	0.08	2
RMSE							0.07	0.14	1.9

D. Latency Experiment.

To evaluate the data communication performance between the proposed localization system, measurements were taken of the latency and time interval between data transmission and reception. The test was conducted by running the ASV automatically in a straight line so that the waterflow sensor could record movement data consistently. The parameters observed included the time it took for the water flow sensor output value to appear on the serial monitor, the time it took for the data to be received by the GUI, and the calculation of latency and time interval between data.

Based on the test results shown in Table 5, the average latency between data transmission by Arduino Mega 2560 and data reception by GUI was 113.6 milliseconds. This value shows that the data communication process is fast enough and can be used for real – time monitoring process.

TABLE V
LOCALIZATION LATENCY EXPERIMENTS RESULTS

No	Arduino Timestamp (*ms*)	GUI Timestamp (*ms*)	Latency (*ms*)	Arduino Interval (*ms*)	GUI Interval (*ms*)
1	67	150	83	-	-
2	100	202	102	33	52
3	133	256	123	33	54
4	199	311	112	66	55
5	232	366	134	33	55
6	299	419	120	67	53
7	365	474	109	66	55
8	398	529	131	33	55
9	464	582	118	66	53
10	531	635	104	67	53
Average			113.6	51.56	53.89

The average data transmission interval from Arduino Mega 2560 is 51.56 milliseconds and data reception by the GUI is 53.89 milliseconds, indicating a consistent communication frequency with a slight time difference. Although, there are variations in the interval on the Arduino side (33 – 67 milliseconds) due to internal processes such as sensor reading or buffer queuing, the GUI is able to receive and display data consistently. Overall, these results show that the designed system is capable of sending and displaying sensor data in real - time.

E. Limitations and Future Work.

The proposed localization system shows promising results in calm water conditions, without any external disturbances. However, this localization system has several limitations. This system has not been tested in dynamic environmental conditions such as strong currents, surface waves, or weather disturbances, because this system is designed specifically for calm waters where maritime competitions are often held. In addition, this localization system has not undergone specific robustness testing against common real-world disturbances such as noise, sensor misalignment, or data dropout.

The next phase of work will involve testing the system in open waters with more challenging environmental conditions. Additional evaluations will also be conducted on noise, sensor installation errors, and data loss. The linear regression method used in this localization system has the potential to be integrated with the Kalman Filter method to produce more accurate and stable distance estimation. This system will also be further developed to enable integration with autonomous navigation systems.

IV. CONCLUSION

Based on the results and analysis, this research successfully develops a localization system for the ASV using waterflow sensors optimized with linear regression method and integrated with orientation (yaw) from IMU sensor using sensor fusion. This research includes four experiments, IMU BNO055 experiment, waterflow optimization, and ASV global position experiment, and latency experiment. In IMU BNO055 experiment, the actual yaw is varied at 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. The RMSE value obtained from the experiment is 1.54° degrees. Waterflow sensor optimization experiment is carried out by moving the ASV straight at actual distances of 0, 2, 4, 6, 8, and 10 meters. The results of the experiment showed significant difference in accuracy, where RMSE value of 161.65 meters decrease to 0.28 meters. After being optimized using linear regression method. In ASV global position experiment, the ASV moves straight forward at yaw angle of 65° to the left, resulting in RMSE value of 0.07 meters in the X-axis and 0.14 meters in Y-axis. The results of the communication latency evaluation show that the average delay between data transmission by the Arduino Mega 2560 and reception by the GUI is 113.6 milliseconds. Additionally, the system has a stable data transmission interval of 51.56 milliseconds on the Arduino side and 53.89 milliseconds on the GUI side, indicating that the system is capable of operating in real-time. Based on the experimental results, the developed localization system showed a high level of accuracy with an RMSE value of less than one meter on the X and Y axes. The designed graphical user interface (GUI) was able to display and monitor sensor data effectively. This system is a potential alternative solution for ASV implementation in calm water environments, such as those often founds in maritime competitions.

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