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Design and Implementation of Sensor Systems for Localization of the Autonomous Robot in a Building Area

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A B S T R A C T

One of the popular studies recently is about social robots that have been implemented in several public areas such as offices. The robot is an employee or worker assistant robot in the Telkom Surabaya Institute of Technology building to help carry out the work of delivering packages to the destination according to the tasks given. The problem that often occurs is an error in the robot's localization system causing the robot's movement to the target point to experience a position error. This research contributes to the comparative evaluation of 2 localization methods on mobile robots, namely the first is the use of a rotary encoder sensor and the second is the use of sensor fusion based on the extended Kalman filter implemented on the robot prototype. This study aims to develop a sensor system that is adapted to the design of the robot and the environment in which the robot is tested and to find out the comparison of the two methods. The use of extended Kalman filter-based sensor fusion can provide more accurate results in robot localization, especially when moving on complex paths. Sensor fusion enables the combination of several sensors such as rotary encoders and IMU (Inertial Measurement Unit) sensors to provide more complete and accurate information about the position and orientation of the robot. In this study, sensor fusion successfully reduced the localization error of the robot to 0.63 m when moving straight and 0.29 m when moving on a complex path, compared to the use of a single sensor which resulted in a larger error of 0.89 m. Based on the study that has been conducted, it can be considered as a potential solution in the development of other social robots to improve the accuracy and performance of the robots when performing certain tasks in the future.

INTRODUCTION

The role of humans in performing monotonous work for a long time requires concentration and precision that can make employees tired, reduce concentration at work, and reduce work enthusiasm [1][2]. These factors can be in the form of human error [1][3]. Therefore, to reduce human error in the office, some companies provide office assistant facilities in some buildings to serve all the needs of office employees, such as delivering reports or letter files, food, and logistical needs [4]. However, this will affect the company's expenditure because it has to pay a salary or honorarium for office employees. With the development of current robotics technology, it is easier to develop technology to replace human roles in carrying out tasks such as delivering heavy packages, food, or other equipment within the building area more efficiently and safely. In today's technological era, many intelligent devices can help simplify human daily activities in the office, such as Search engines, the Internet of Things (IoT), robotics, Artificial Intelligence (AI), and Renewable energy [5].

Another study has been conducted on the development of an autonomous robot system using the Simultaneous Localization and Mapping (SLAM) method to plan an indoor rescue path using a wheeled robot [6]. The robot system uses STM 32 as the brain to receive encoder and gyroscope data information, as well as sensors. LiDAR is used for mapping, and an RGB camera is used for detecting images of conditions in the room [5][7]. Additionally, in 2019, research was conducted on building autonomous robots for outdoor radiation and video surveys [8]. The robot was also designed to detect radiation and obstacles while navigating around the affected area in a nuclear power plant [9][10]. With these developments, continuous improvement can be made in the company's industry to serve the needs of office staff in the current industrial era.

Based on the aforementioned reasons, this study aims to design and implement localization using a combination of Rotary Encoder & IMU sensors on the Robot in the ITTelkom Surabaya Building area to assist staff or lecturers in delivering goods or documents to the desired room. Robot is a delivery service robot. Some studies have also used sensor fusion techniques to improve localization [11]-[14]. The combination that is more commonly used is a vision-based combination which can be influenced by

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several external factors such as lighting, orientation, and range[15]-[19]. Robot uses two sensors for localization: Rotary Encoder and IMU. The results obtained from the sensors will be compared during localization with one sensor and after using sensor fusion (Rotary Encoder & IMU). Sensor fusion has been implemented for various robot applications to reduce localization errors on the robot [20]-[22].

The sensor system uses the Extended Kalman Filter (EKF) algorithm to combine two sensors (Rotary Encoder & IMU) to improve robot localization. The analysis of localization errors is conducted when using only the Rotary Encoder and when using sensor fusion between the Rotary Encoder and IMU. This study conducts a comparison between the use of one sensor and the combination of 2 sensors in the environment where the robot is being tested.

The benefit of this research is to assist employees in delivering goods to different rooms using Robot , making it more efficient in terms of time, cost, and energy.

METHOD

In research on spatial mapping using LiDAR-based Simultaneous Localization and Mapping (SLAM) method, the robot encounters navigation difficulties [11][24]. Apart from using LiDAR to obtain accurate mapping and assist in precise localization, there are other ways to do so, such as improving the robot's navigation capabilities using image processing technology. However, this technology is not suitable for use in dirty or dusty terrain conditions as it interferes with the resulting image processing. Therefore, the LiDAR sensor becomes a reliable solution for obtaining precise mapping in field conditions with all types of lighting. Experimental results show that the LiDAR sensor can work well by providing distance data, several angles, and scanning frequency according to its specifications. Calculating the number of angles is done by utilizing the start bit data generated by the sensor and testing the number of angles. This start-bit data is used as a reference for the sensor when starting the scanning process. Hence, it can be concluded that the LiDAR sensor used is suitable for use in any field conditions [11].

Another research approach involves the use of GPS, IMU, and visual odometry equipped with a Kalman filter [25]. The system works by obtaining heading angle information and angular velocity from the IMU's magnetometer and then obtaining absolute position information from the mobile robot's GPS. Image-based visual odometry is used to obtain additional localization information and moving distance. The sensor data is combined with the EKF (Extended Kalman Filter) algorithm to obtain a more precise robot position. In the beginning, visual odometry provides reliable information. However, as the robot moves and the amount of position data increases, errors caused by environmental factors may lead to inaccurate distance and direction data. Nevertheless, using GPS information can correct distance errors and produce accurate map results. The IMU provides good directional information, leading to appropriate mobile robot position accuracy [26].

The mobile robot equipped with a 2D LiDAR sensor can use the 2D SLAM algorithm to perform mapping and localization tasks in indoor environments for software parts [4]. The ROS system is used to process the mapping data obtained from laser scans via ROS Visualization (RViz), while MATLAB software is utilized to analyze the accuracy of the maps generated by the sensor scans in comparison with the actual map measurements. The LiDAR sensor scans the unknown environment and visualizes it on the RViz platform. Consequently, the mapping and localization of the robot are performed using the Tight remote-control software [27].

This study builds upon some of the previous research and focuses on the design and implementation of localization using a combination of rotary encoders and IMU sensors on the Robot, which can navigate the robot to a desired location within a building. By using these components, the robot can detect its surrounding environment more accurately and navigate to the desired location with the help of the EKF (Extended Kalman Filter) algorithm. The microcontroller used is Arduino, and Jetson Nano serves as a mini PC running on Linux OS and ROS, acting as a serial link between Arduino and Jetson Nano.

The research aims to design a localization algorithm by implementing a combination of Rotary Encoder & IMU sensors on Robot in the building area of Telkom Institute of Technology Surabaya. The hardware design includes the system design of Robot, mechanical design, and electronic component design that will be used to combine the two sensors.

Localization System

Localization is achieved by combining encoder and IMU sensors to produce precise odometry data. As shown in Figure 1, the Localization process in the surrounding area involves determining the robot's initial position through sensor fusion, which combines Rotary Encoder and IMU data. To move the robot to a predetermined position (x, y), the teleop_twist_keyboard is used as a remote control on the laptop to send commands to the robot. When the robot reaches the intended position (x, y), the ROS visualization displays the odometry data of the robot's movement as it moves towards the intended point. The correct position data of the robot can be obtained by using the "rostopic echo Odom" command in the ROS terminal. This command displays the combined robot position movement data in the form of x, y, and z.

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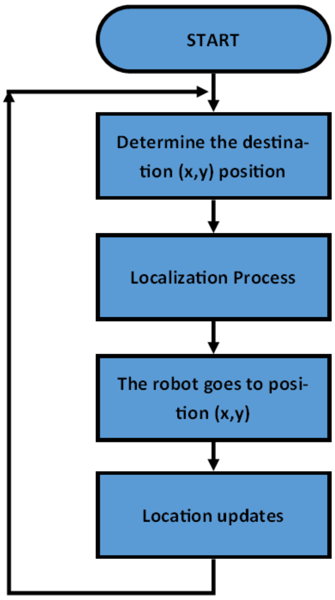

Figure 1. Flowchart of robot localization system

Design System

This section describes the mechanical and electronic circuit design of the robot. The mechanical design includes the main body, frame, and object placement of the robot. The electronic design involves assembling the circuit used in the robot.

The Arduino Mega receives input from the Jetson Nano to control the movement of the DC motor. The system design in Figure 2 shows how to integrate the components used in the robot. Figure 3 is a robot designed using Solidworks software, then realized using an aluminum plate and an aluminum profile. The following is a design image of the robot.

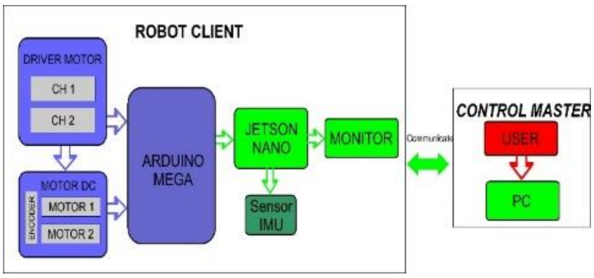

Figure 2. Block diagram of the system

The robot is equipped with a LiDAR sensor and a monitor screen, which are mounted on top of the robot using 3D printing materials. As shown in Fig. 3 and Fig. 4, the robot has four wheels, with two rear wheels for driving and two front wheels free, allowing the robot to move in all directions. The frame is made of 25 mm x 25 mm aluminum profile, while the body frame cover is made of a 3 mm thick aluminum plate. This material was chosen due to its resistance to rust, lightweight, and easy-to-shape properties, making it suitable for use on robot designed to carry objects.

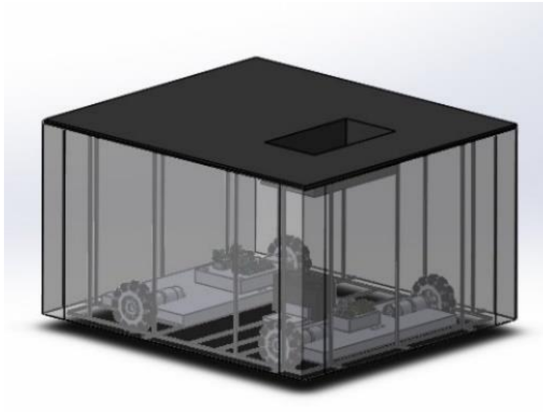

Figure 3. Robot visual design

Figure 4. Robot's actual design

Fig.5 is the circuit used in the delivery service robot, which employs the Arduino Mega 2560 as a microcontroller, the IBT driver as the input for the DC motor, and the encoder sensor connected to the Arduino Mega to read the distance of the robot's movement. Additionally, a 24V battery is used.

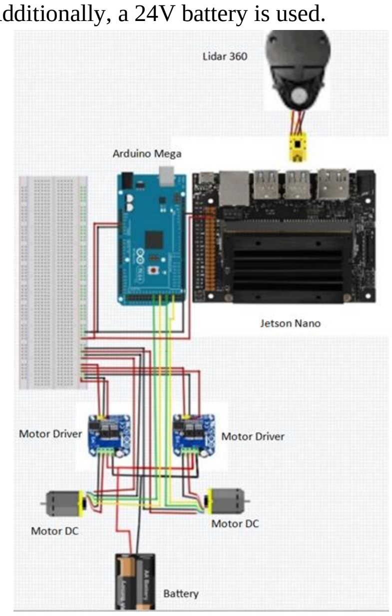

Figure 5. Device schematic from Robot

The system was implemented with two types of experiments: one using a single sensor to generate odometry, and the other integrating two data sources, namely odometry and orientation from an IMU sensor, as shown in the Fig.6.

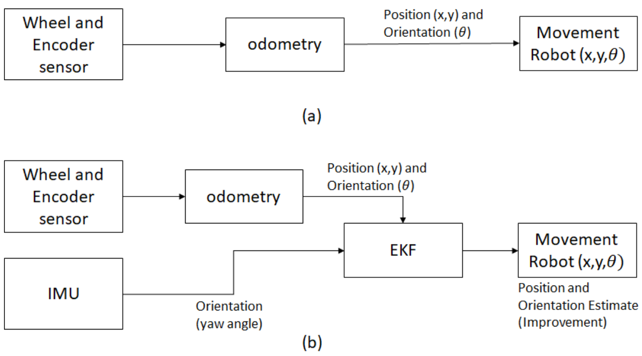

Figure 6. The system diagram consists of two parts: (a) Single Sensor and (b) Fusion Sensor

Sensor Fusion

The robot's position and orientation are determined using a rotary encoder sensor while the robot moves to its position. In order to move to a predetermined position, the robot must know the orientation angle of its position in the room. The angle of the x and y orientation is then determined while moving to maintain its constancy using the IMU sensor. By combining the two sensors, the odometry movement results can be more consistent in the x-movement angle, thereby minimizing the occurrence of y-angle error movements when the robot moves straight.

The rotary encoder is a sensor that is used to detect the direction and position of movement of a DC motor. It consists of three interconnected components: a perforated disc, LED light, and optical sensor. The disc has a hole attached to the motor's movement so that when the motor moves, the perforated disc also moves. Thus, when the DC motor moves, the sensor will generate a pulse signal because the LED emits light on the photodiode, which turns on and off when passing through the disc's hole alternately [28]. Between the discs are LED sensors and optical sensors acting as transmitters and receivers. The following equation can determine the speed of the robot.

$$V = \frac{S_t - S_{t-1}}{|T_t - T_{t-1}|} \quad (1)$$

In (1), where V = Speed (m/s), S_t= Current distance traveled (m), S_{t-1} = Previous distance (m), T_t = Current time (s), T_{t-1} = Previous time (s). The robot's position is to use a constant variable to change the number of counters obtained by the encoder sensor into the distance traveled by the robot [29]. Constants can be obtained using the following equation.

$$C = \frac{K\ wheel}{Encoder\ Resolution} \quad (2)$$

In (2), where C = Constant variable (mm/ counter), K wheel = Circumference of the wheel (mm), Encoder Resolution = Number of counters one revolution. The distance traveled on the left, and right wheels are initialized with the variables M_left (3) and M_right (4). The distance between the left and right wheels is initialized with d. The determination of rotation and distance traveled, it can be determined using the following formula (5) and (6).

$$M\_left \quad = counter\_left\ x\ C \quad (3)$$

$$M\_right \quad = count\_right\ x\ C \quad (4)$$

$$distance = \left(\frac{M\_left + M\_right}{2}\right) \quad (5)$$

$$\theta = \left(\frac{M\_left - M\_right}{d}\right) \quad (6)$$

IMU sensors are commonly used to detect Euler angles roll, pitch, and yaw [30]. In this study, the dominant Euler angle is on the z-axis, known as the yaw angle, which relates to the orientation movement of the robot. The movement of a ground robot is represented in position (x, y) and orientation (theta), whereas aerial robots require all Euler angles, including pitch, roll, and yaw.

$$yaw = artan\left(\frac{\sqrt{(x)^2 \ + \ (y)^2}}{z}\right) x \left(\frac{180}{\pi}\right) \quad (7)$$

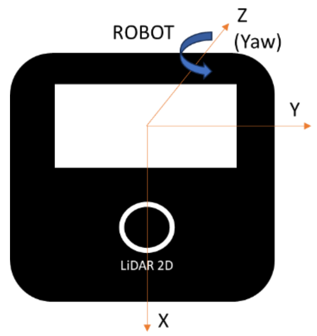

Figure 7. Illustration of the yaw angle in the robot frame

In (7), where x = x-axis Accelerometer Value, y = y-axis Accelerometer Value, z = z-axis Accelerometer Value, and π=3.14. Extended Kalman Filter (EKF) is a Kalman filter based on particle filtering. EKF processes estimates of the current position or state based on previously stored information [31][32].

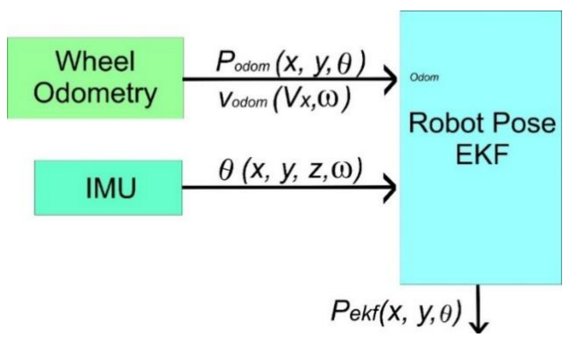

Figure 8. EKF algorithm on robot

By utilizing the EKF algorithm for sensor fusion between the rotary encoder and IMU, the robot's movement can be linear and generate smaller errors compared to only using a rotary encoder sensor. The algorithm involves using the f function to calculate the previously predicted state and the h function to calculate the measurement of the predicted state.

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The way to get the linear velocity of the robot and the angle of the robot's odometry is by using the odometry data in the ROS. The data has been published in the topic raw_odom. In raw_odom, it is also used to calculate the change in angle and location over time. As a solution using the EKF package, the rotary encoder speed is combined with the IMU orientation data, which is published in the IMU/data topic using EKF. The formulation of EKF can be defined as follows.

$$X_k = f(X_{k-1}, v_k) + v_k \quad (8)$$

$$Z_k = h(X_k) + v_k \quad (9)$$

In (8) uses the transition function f to connect the state vector at the previous time, X_{k-1}, with the input or disturbance v_k, which represents the uncertainty or noise in the system model. By applying the transition function f to the previous state vector and adding the disturbance variable v_k, this equation obtains an estimation of the state vector at time k, taking into account the uncertainty in the system. Then, in (9), Z_k represents the observation vector at time k. The function h is the observation function that relates the state vector X_k to the expected observation vector. The variable v_k represents the disturbance or noise variable that represents the uncertainty in the measurement or observation.

In Fig. 6, the EKF algorithm combines the rotary encoder sensor with the IMU. The EKF processes the Odom position sent to the Wheel Odometry, which includes the Odom position $P_{odom}(x, y, \theta)$and the Odom Velocity $v(V_x, \omega)$. Meanwhile, the IMU sensor sends orientation data θ (x, y, z, ω) to the EKF pose robot to filter out any noise in the sensor and ensure that the data is not lost during the estimation process. After being processed by the EKF pose robot, the odometry data produces the EKF P_{ekf}(x, y,θ) position of the Robot.

RESULTS AND DISCUSSION

Testing Linear Robot Movement Using Rotary Encoder

The precision test for robot's movement uses an encoder sensor as odometry to determine changes in the robot's position during movement. The results of the odometry movement are then compared with a meter-measuring instrument at a predetermined distance. The test was conducted from 1 to 20 meters, with five trials carried out for each distance. The comparison results of the robot's movement experiment are presented in a graph on the X and Y axes. The experiments were conducted five times (P1, P2, P3, P4, P5). From the movement graph, it can be observed that the movement error increases with the distance traveled from the starting point, which is evident in all five trials (P1 to P5). The experiment resulted in an average total error of 0.89 meters. The graphic data is shown in Fig. 9.

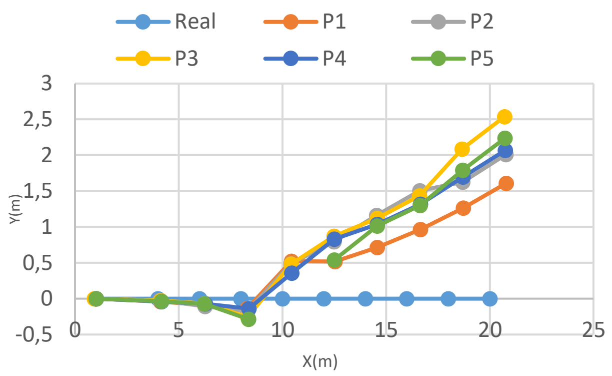

Figure 9. Robot localization experiment when walking straight for 20 m with a rotary encoder sensor

Testing Linear Robot Movements When Using Fusion Sensors, namely IMU & Rotary Encoder

The Robot testing involves a combination of two sensors, namely a rotary encoder and an IMU, which have been converted into odometry data of the robot's movement. The automatic data retrieval process is the same as the previous experiment, which only used a rotary encoder sensor. The movement results of the robot will be compared using only a rotary encoder and a combination of both rotary encoder and IMU sensors. The results of the linear movement of the robot using a combination of both rotary encoder and IMU sensors with five trials are shown in Fig.10.

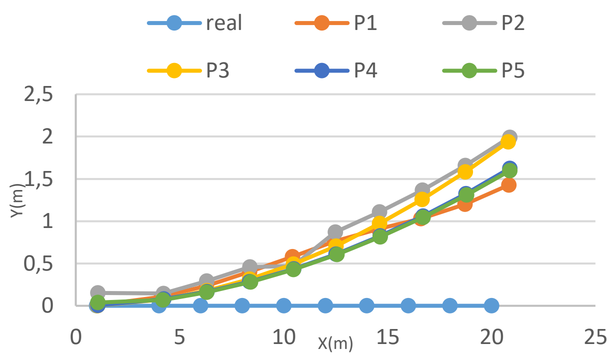

Figure 10. Robot localization experiment when walking straight for 20 m with a combination of rotary encoder sensor and IMU

Data from Fig. 10 shows that the further the robot moves from its starting position, the larger the positional error that occurs. This experiment resulted in an overall average error of 0.63 meters. However, this is still an improvement compared to using only a rotary encoder.

Testing the Movement of the Robot to Form a Square Using a Rotary Encoder Sensor

Sensor rotary encoder conducted a test on the robot when it moves to form a square and aimed to determine the accuracy of the robot's movement when navigating in a room in the form of a hallway or a large room. This test will be carried out by moving the robot on a path marked with duct tape and then giving the size to form a 2 x 1-meter box. The robot's movement results will be analyzed and then compared with the predetermined distance. This experiment resulted in a total average error of 0.86 meters.

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After that, they tested the error from the robot's movement when navigating autonomously. Fig. 11 and 12 are the results of the graph generated by the robot when forming a square.

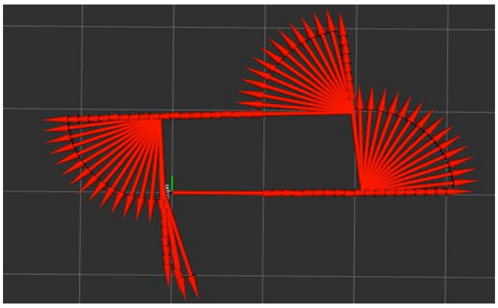

Figure 11. Robot localization experiment while walking all four points. The sensor used is a rotary encoder which is displayed on the rviz

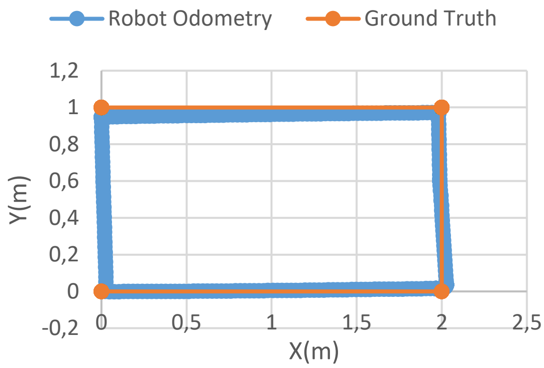

Figure 12. Comparison of the actual localization with the localization of the designed system of a single sensor

Testing the Movement of the Robot Forming a Square Using Fusion Sensors (Rotary Encoder & IMU)

Fig. 11 and 12 depict the robot's movement results when using a combination of rotary encoder and IMU sensors. The tests conducted were the same as before, where the robot moved to form a square from position x: 0.0 m and y: 0.0 m. The robot moved from the starting position A to position B with actual distances of x: 2.0 and y: 0.0. Then, from position B, the robot moved to position C with an actual distance of x: 2.0 and y: 1.0, resulting in the robot's distance coordinates of x: 1.9815 and y: 0.9365. Subsequently, the robot moved to position D with actual distances of x: 0.0 and y: 1.0. The robot's movement at point D was x: 0.00241 and y: 0.8945. This experiment resulted in a total average error of 0.29 meters. This indicates a significant improvement compared to using a single odometry sensor without orientation correction, as demonstrated in this research [33].

CONCLUSIONS

This study successfully designed and implemented precision sensors for localizing the Autonomous Robot in the Telkom Institute of Technology Surabaya building area. The research findings showed that localization was successful and more accurate when using a combination of a rotary encoder sensor and IMU with the ROS platform compared to using only a rotary encoder. Initially, the system design using only a rotary encoder allowed the robot to move straight to the destination point up to a distance of 20 meters with an error of 0.89 meters, and when moving in a square, it resulted in an average error of 0.86 meters. On the other hand, the orientation error generated when using only one IMU sensor was 0.030725 degrees. In contrast, the system design with sensor fusion was successful, with an average error of 0.63 meters when moving straight and an average error of 0.29219 meters when the robots moved to form a square. The use of sensor fusion resulted in smaller errors in robot movement compared to using only a rotary encoder. The orientation error generated when using sensor fusion was also minimal, namely 0.020 degrees. Furthermore, the localization system with sensor fusion was found to be superior when the robot moved straight for 20 meters compared to using a single sensor. The combination of the two sensors revealed that more position errors were caused by orientation problems, such as slippery conditions in the area leading to wheel slippage. These problems can be resolved by incorporating the orientation information from another sensor, in this case, the IMU sensor, to improve the performance of the localization system..

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