Autonomous Package Delivery Car Robot System with 2D Point Cloud Reconstruction and Object Detection as A Logistics Delivery Robot

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***Abstract*—This research develops an autonomous package delivery car robot system using the A* algorithm on 2D Point Cloud data from LIDAR and object detection with YOLO. The pathfinding system using the A* algorithm successfully navigates the robot with a success rate of 100%, an average processing time of 1.6 ms, and an average cost of 8.09. The robot is designed with specifications of operating temperature of -40°C to +85°C, operating time of 180 minutes, and maximum payload capacity of 5 kg. Object detection testing using YOLOv4-tiny on 2D Point Cloud resulted in an Average Precision (AP) of 100% for cars and humans, 92.74% for motorcycles, with a detection sensitivity of 68.3%. The distance prediction system has 97% accuracy, with an average prediction difference of 0.092 meters. This research shows that the application of the A* algorithm to 2D Point Cloud data improves the efficiency and accuracy of robot movement, and makes a significant contribution to the development of autonomous vehicles for logistics applications.**

***Index Terms*—Autonomous robot, Object detection, Pathfinding A*, YOLOv4-tiny, 2D Point Cloud.**

I. Introduction

In recent years, the adoption of autonomous vehicle technology across various industrial sectors has shown significant growth, particularly in enhancing operational efficiency [1]. One specific application under development is the use of autonomous vehicles for logistics delivery within proximally located sites. PT Bacarthas, a company operating in the telecommunications field, faces challenges in delivering logistics packages between Base Transceiver Stations (BTS), which require both speed and high efficiency due to the management of BTS locations spread across relatively close areas with diverse route complexities [2].

Autonomous package delivery robots emerge as an innovative solution to address these needs. Equipped with navigation systems powered by intelligent algorithms and real-time mapping capabilities, these robots are expected to optimize logistics distribution between BTS locations [3]. This technology not only improves delivery speed and accuracy but also reduces the risk of human errors that often lead to inefficiencies in logistics operations.

A key component of the autonomous package delivery robot is the navigation or path-finding system, which is responsible for determining the optimal route based on mapped environments [4]. In the context of BTS areas that often have dense and complex routes, the system must quickly comprehend route maps and make precise decisions to reach the intended destinations. The integration of environmental data through 2D Point Cloud reconstruction, combined with object detection technologies such as YOLO (You Only Look Once), is a strategic approach to enhance the reliability of this system [3][5].

The navigation system is designed using data from LIDAR (Light Detection and Ranging) sensors to produce two-dimensional (2D) environmental maps [4]. This data is then analyzed using the A* algorithm, known as one of the most effective methods for finding the shortest path in complex search spaces [2]. By considering efficiency and accuracy, the A* algorithm combines heuristic distance estimates with the exploration of potential routes to deliver optimal navigation decisions [2][5].

The implementation of object detection via YOLO also plays a critical role in ensuring the safety and adaptability of the vehicle in real-time situations [3]. YOLO enables rapid identification and recognition of objects surrounding the robot, reducing the likelihood of collisions or navigation errors that could impede logistics delivery between BTS sites [5].

This research aims to develop and test a navigation system based on the A* algorithm integrated with environmental reconstruction using 2D Point Cloud data from LIDAR

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sensors and object detection through YOLO [2]-[4]. Through this development, the autonomous package delivery robot is expected to support PT Bacarthas's operations in enhancing the efficiency of logistics delivery between BTS locations, which, despite their proximity, require the management of complex routes [2][5].

The outcomes of this research are also anticipated to make a positive contribution to the development of autonomous vehicle-based solutions for industrial needs, particularly in the telecommunications logistics sector [1][3]. Furthermore, this study has the potential to open collaborative opportunities between technology companies and industrial sectors to create innovations relevant to market demands. Thus, the development of this autonomous package delivery system is envisioned as a foundational step towards broader-scale autonomous technology optimization [1][5].

II. Related Work

Research on autonomous vehicles has gained substantial attention due to its potential to enhance operational efficiency across various industries. Early studies, such as the DARPA Urban Challenge, laid the foundation for developing autonomous navigation systems by demonstrating the feasibility of autonomous vehicles in complex urban environments [1]. Building upon these foundational efforts, researchers have explored various path-finding algorithms and real-time object detection technologies to address specific challenges in autonomous navigation.

The A* algorithm is widely recognized for its effectiveness in solving complex path-finding problems. Cheng et al. [6] demonstrated its application in unmanned ground vehicles, highlighting its ability to determine the shortest path with high accuracy in diverse search spaces. Furthermore, the integration of heuristic techniques with A* has been shown to enhance the algorithm’s computational efficiency, making it suitable for real-time navigation in robotics. Modern adaptations of A* incorporate machine learning techniques to further optimize route planning by learning patterns from historical data, which can significantly improve decision-making in dynamic environments.

In parallel, advancements in LIDAR technology have revolutionized environmental mapping by providing accurate 2D and 3D reconstructions of surroundings. Jain et al. [3] discussed the integration of LIDAR with artificial intelligence (AI) to improve robotic navigation. Their findings revealed that combining LIDAR data with AI algorithms significantly enhances the robot’s ability to adapt to dynamic environments. Recent studies also explore the fusion of LIDAR with other sensors, such as RGB cameras and inertial measurement units (IMUs), to create more robust and detailed environmental models, especially in challenging terrains.

For object detection, YOLO (You Only Look Once) has emerged as a state-of-the-art algorithm due to its real-time performance and high accuracy. Redmon and Farhadi [4] developed YOLOv3, which offers an incremental improvement over earlier versions, enabling rapid identification of multiple objects in real-time scenarios. This technology has been widely adopted in robotics for ensuring safety and optimizing navigation in environments with dynamic obstacles. Extensions of YOLO, such as YOLOv5 and YOLOv8, provide improved precision and efficiency, enabling robots to detect smaller and partially occluded objects, which are common in cluttered operational areas.

Combining A* and YOLO with LIDAR data offers a comprehensive solution for autonomous navigation in complex environments, such as Base Transceiver Station (BTS) logistics. Studies by Thrun et al. [5] have underscored the importance of probabilistic approaches in enhancing the reliability of robotic systems. By leveraging probabilistic robotics, robots can better handle uncertainties inherent in dynamic and unstructured environments. Probabilistic path planning, for instance, accounts for variable traffic conditions and unpredictable obstacles, ensuring smoother navigation and task execution.

The integration of these technologies has been instrumental in addressing logistics challenges, such as those faced by PT Bacarthas. The specific focus on delivering logistics packages autonomously between BTS sites necessitates a robust and reliable navigation system. The proposed approach combines the strengths of A*, YOLO, and LIDAR to provide an efficient and scalable solution tailored to the unique requirements of the telecommunications logistics sector. By incorporating real-time communication protocols, such as Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) systems, the proposed design further optimizes route coordination and safety management.

Moreover, recent developments in edge computing have opened up opportunities for deploying complex algorithms like A* and YOLO on small embedded devices within autonomous robots. Edge-based solutions reduce latency by processing data locally on the robot, as highlighted by Lee et al. [7], ensuring faster response times and independence from cloud-based systems. This advancement is crucial for mission-critical tasks, such as logistics, where delays can disrupt the overall workflow.

One prominent application of this technology is in the field of intralogistics within factory settings, as demonstrated by Kondo et al. [8]. Their research showcases how autonomous mobile robots (AMRs) equipped with LIDAR and YOLO [9]-[11] navigate warehouses efficiently while avoiding collisions with workers and other robots. These lessons can be extrapolated to outdoor logistics environments, such as BTS sites, to optimize delivery tasks while ensuring operational safety. Furthermore, scalability and energy efficiency remain pressing challenges for autonomous systems. Sustainable solutions, such as the integration of solar-powered charging stations for autonomous robots, have been proposed by researchers [12]-[15]. These innovations ensure that deployment of autonomous vehicles is not only operationally efficient but also environmentally friendly.

The combined use of A*, YOLO, and LIDAR, alongside supportive technologies such as V2I, edge computing, and sustainable power solutions, represents a significant leap forward in autonomous logistics. This comprehensive system is poised to address the intricate logistics requirements of PT Bacarthas and similar organizations by delivering high precision, adaptability, and efficiency in challenging operational scenarios.

III. Method

This section describes the methodological approach applied in the research of developing an autonomous package delivery car robot system for logistics delivery between Base Transceiver Station (BTS) sites with 2D Point Cloud reconstruction and object detection technology. The methodological steps used include the stages of system design, data collection, hardware and software development, simulation, and performance evaluation.

A. System Design

The system designed in this research includes three main components, namely hardware, software, and system architecture. In the hardware aspect, LiDAR sensors are used to reconstruct the environment in 2D, embedded processing units such as Raspberry Pi, and wireless communication modules that support coordination between base stations. On the software side, the implementation of the A* navigation algorithm is used for path planning, while object detection is done with the integration of the YOLO algorithm. In addition, there is a speed and direction control module based on a real-time operating system (RTOS). The system architecture is designed in such a way as to be able to integrate sensor data and artificial intelligence algorithms on an autonomous platform, thus allowing the robot to move safely in an environment with various real constraints.

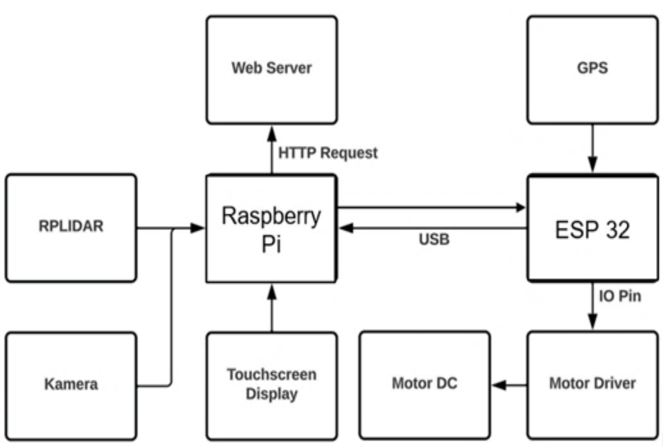

Fig. 1. System Design.

B. Data Collection

The data required for the development and testing of the system algorithms was collected through a series of structured processes. The collection of environmental reconstruction data involved the use of LIDAR sensors capable of generating 2D environmental maps of the study area, including routes connecting base stations with different types of terrain. Visual dataset collection was done through direct observation in the field, aiming to train the YOLO algorithm in detecting objects such as vehicles, road signs, and pedestrians. During the trial, system performance parameters were comprehensively measured, including travel time, power consumption, and navigation accuracy, to evaluate the effectiveness of the design.

C. Testing and Evaluation

Before testing in the real world, simulations are conducted to test the algorithm on virtual conditions. In the simulation stage, a virtual environment is built using software such as Gazebo or MATLAB to validate the performance of the pathfinding and object detection algorithms. Simulation of the algorithm is performed by generating a 2D Point Cloud reconstruction of the test area virtually, with random placement of obstacles by the system. This approach aims to observe the reliability of the pathfinding algorithm in recognizing and avoiding obstacles in real-time.

After successful simulation and satisfactory performance, a real-world test was conducted. This test uses ordinary road conditions with low traffic, such as in residential neighborhoods or areas around BTS. This test environment was chosen to assess the system's ability to deal with real conditions that include varied terrain and the possible presence of dynamic objects. The evaluation of the real-world test includes navigation speed, object detection accuracy, as well as the system's response to changes in live environmental conditions.

A performance evaluation of the system was conducted to assess its success using several key parameters. Detection accuracy is one important aspect, which is measured based on the success rate of the YOLO algorithm in detecting objects. In addition, the system's performance in pathfinding was evaluated through the effectiveness of the A* algorithm in determining the optimal route as well as its ability to avoid obstacles in the test environment. Another parameter is the system interface, which is assessed by the ease of integration and responsiveness between hardware and software. The results of this evaluation are analyzed to determine if the system has achieved the desired performance. If deficiencies are found, the system will be refined in the next iteration to increase its efficiency.

IV. Result

A. Navigation System

The navigation system in the autonomous vehicle developed in this research has demonstrated success in various aspects, both in terms of technology and field performance. A key component of this system is the utilization of query results from the Google Direction API, which provides real-time route information. The data produced by this API includes parameters such as "end_location" and "maneuver," offering guidance on when the vehicle should turn and how to adjust its route based on road conditions. This integration allows the vehicle to adaptively understand the route, which is crucial for navigation in dynamic and complex environments.

In addition, this navigation system relies on environment reconstruction based on point cloud data generated by LiDAR sensors. This technology detects the road boundaries around the vehicle, providing detailed visual data about the environment. This information is used to ensure the vehicle stays on a safe path. In this process, the point cloud mapping results are combined with the Google Direction API query results to create more accurate guidance. With this approach, the vehicle can optimally adjust its position and direction to follow the designated route, even as road conditions change.

The use of GPS sensors is also a critical element in this navigation system. The location data produced by the GPS allows the vehicle to accurately determine its position along the route. The GPS sensor is connected to an Arduino UNO to process and transmit location data to the vehicle control system. However, this study found that GPS signal locking time can be a challenge, especially during the daytime. Based on the tests, the average signal locking time during the day is 194.86 seconds, while at night, it is only 45.24 seconds. This delay is caused by the GPS initialization process, which requires time to connect to satellites. Therefore, the system is designed to wait up to 250 seconds to ensure valid location data before transmitting it to the web monitoring service. This approach helps maintain the accuracy and reliability of navigation.

The pathfinding system used in this vehicle is designed based on the A* algorithm, with diagonal movement restricted to match the conditions of a self-driving vehicle. In this context, diagonal movement is considered impractical due to the vehicle's physical limitations in following sharp-angled paths. The A* algorithm is implemented to find the optimal route, prioritizing efficiency and safety. The dataset used in the tests includes 384 navigation scenarios, and the results show that the system can find routes with 100% accuracy. The average cost for the entire dataset is 8.09, with an average processing time of 1.6 ms and a maximum of 16.568 ms. These results indicate that the A* algorithm performs highly efficiently in complex environments.

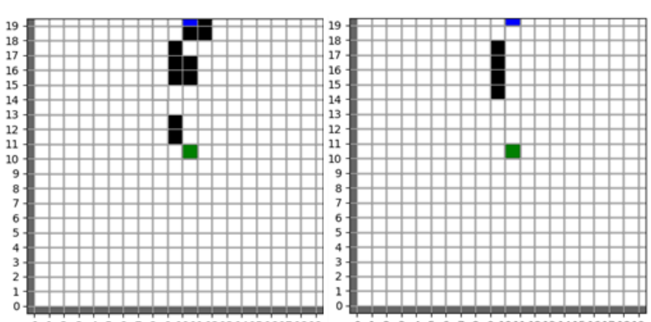

Fig. 2. Dataset.

In addition to navigation, this system is equipped with speed control adjusted based on the vehicle's RPM value and the distance to objects ahead. This data is taken from the point cloud to predict the position of objects one second ahead. This prediction enables the vehicle to adjust its speed in real time, avoiding potential collisions and ensuring a safe journey. Steps in the control algorithm involve observing surrounding objects, labeling the objects, sampling new images, and determining the path based on environmental conditions. This approach provides high flexibility for the vehicle to adapt to various field situations.

The integration of these technologies, including Google Direction API, LiDAR, GPS, and the A* algorithm, creates a reliable navigation system for logistics delivery between Base Transceiver Stations (BTS). This autonomous vehicle can face environmental challenges such as narrow roads, winding routes, and the presence of dynamic objects. However, some technical challenges still need to be addressed, such as slow GPS signal locking times under certain conditions. Potential solutions to this issue include using more advanced GPS modules or integrating faster communication technologies such as 5G networks.

Overall, the results of this study show that the developed navigation system performs excellently in finding routes and avoiding obstacles. The implementation of advanced technologies such as point cloud data and the A* pathfinding algorithm not only improves operational efficiency but also ensures vehicle safety. With 100% accuracy in route-finding, the system meets the needs for fast and reliable logistics delivery. Further development could focus on improving data processing speed and reducing GPS signal locking time to enhance the overall user experience. The results of this research make a significant contribution to the application of autonomous vehicles in the logistics sector, particularly for goods delivery in complex and dynamic environments.

B. *Object Detection Performance*

The object detection performance of the system integrates YOLOv4-tiny pretrained weights and has been thoroughly evaluated to ensure its reliability in detecting objects in real-time. The 2D Point Cloud used in this system is a combination of object detection results and mapping data from LiDAR. Object detection tests aim to assess the system's performance using YOLOv4-tiny's pretrained weights, conducted on 150 images extracted from video footage taken at three different locations in Telukjambe Timur, Karawang Regency. These tests focus on detecting three primary classes: humans, motorcycles, and cars.

Intersection over Union (IoU) was calculated to evaluate the accuracy of the detected objects against manually annotated ground truth images. The results, presented in Table 10, indicate that the system achieves an Average Precision (AP) of 100% for the car class, 92.74% for motorcycles, and 100% for humans. However, the test also reveals a relatively high number of False Negatives (144 objects), reflecting a sensitivity of 68.3% for the system's detection capabilities.

TABLE I
OBJECT DETECTION RESULT

Class	AP	TP	FP
Car	100.00%	80	0
Motorcycle	92.74%	85	15
Pedestrian	100.00%	145	0
FN			144

Average processing time per frame is 0.29 seconds (approximately 3.4 FPS), demonstrating the system's efficiency. With a Recall of 0.88235 and Precision of 0.95, the combined metrics yield an F1-Score of 0.914926, highlighting the system's robust predictive accuracy. The mean Average Precision (mAP) at a 0.5 threshold stands at 97.58%, further emphasizing the system's high detection performance. Detection accuracy is also reflected in the confidence levels, which were averaged across video frames for each detected class.

TABLE II
SUMMARIZES DETECTION ACCURACY DATA ACROSS THREE VIDEO LOCATIONS

Video Location	CAR	Motorcycle	Pedestrian	Avg. Process. Time (s)
Jalan Adiarsa	66.95%	68.41%	60.13%	0.2347
Jalan Babakan Sananga	64.05%	73.18%	65.52%	0.2535
Jalan Galuh Mas	65.3%	61%	65%	0.2433

Further, object detection was extended to predict object distances for the three main classes. This prediction involved calibrating the relationship between the bounding box perimeter and actual object distance. Calibration for the pedestrian class, for instance, used 56 sample images, each containing a single human object, to derive a mathematical model correlating bounding box dimensions to real distances. The equation for this model, derived through analysis, is represented as:

$$y = 24.789x^4 - 251.72x^3 + 974.15x^2 - 1816.6x + 1635.9 \quad (1)$$

The correlation coefficient of 0.9777 signifies a strong relationship, confirming the model's validity. Similarly, models for motorcycles and cars were developed, yielding high correlation coefficients of 0.9223 and 0.9804, respectively. These findings demonstrate the system's ability to predict object distances accurately, with errors averaging 0.075 meters (2.69%) for humans, 0.1375 meters (5.08%) for motorcycles, and 0.0625 meters (2.03%) for cars. Overall, the system's detection accuracy across all classes averaged 97%. The curve represents of all the prediction result and the input distances can be seen in Fig. 3.

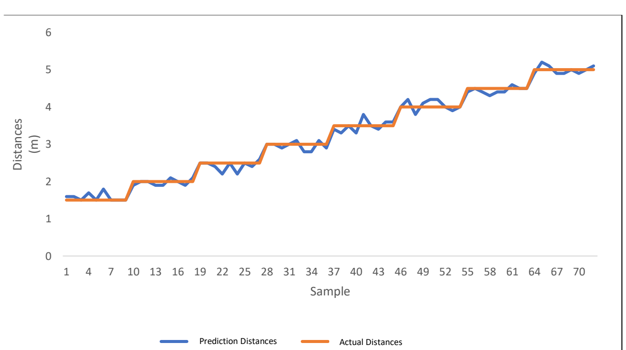

Fig. 3. Prediction vs Real Distances Graph.

C. *Operational Efficiency*

The operational efficiency of autonomous delivery systems far exceeds traditional manual approaches, driving significant improvements across a range of operational metrics. A comprehensive set of tests and analysis revealed several key results that demonstrate the advantages of automation in logistics, especially for deliveries between Base Transceiver Stations (BTS).

The most notable achievement of the autonomous system was the significant increase in navigation speed. By automating the transportation process, the system was able to cut delivery times substantially, directly improving operational efficiency. In a series of 30 delivery routes, the autonomous robot demonstrated a delivery success rate of 80%. Partially failed deliveries were mostly due to external disturbances such as human interference and poor routes resulting in unstable and overturned devices.

V. CONCLUSION

Based on the results of the design and testing of each component, the following conclusions are obtained: (1) This research successfully designed a package delivery autonomous robot car with specifications of operational temperature of -40°C to +85°C, operating time of 180 minutes, and maximum payload capacity of 5 kg. The robot uses LIDAR and YOLOv4-tiny for object detection, with an operation sample time of 1.5 seconds. (2) Testing the object detection system using YOLOv4-tiny on 2D Point Cloud resulted in Average Precision (AP) values of 100% for cars and humans, 92.74% for motorcycles, and detection sensitivity of 68.3%. Recall, Precision, and F1-Score values are 0.88, 0.95, and 0.91, respectively, with a mean Average Precision (mAP) of 97.58%. The distance prediction system has an accuracy of 97%, with an average prediction difference of 0.092 meters. (3) The Pathfinding system showed excellent performance with a 100% route success rate, with an average cost of 8.09 and an average processing time of 1.6 ms.

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