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Empirical Evaluation of IoT-Based Smart Load Delivery Robot for Real-Time Payload Performance Monitoring and Analysis System

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Abstract

Introduction/Main Objectives: The aim of the study was to evaluate the performance of an IoT-based smart delivery robot utilizing the Arduino Nano microcontroller and to analyze the delivery speed achieved by the smart delivery robot compared to the manual delivery method.

Background Problems: Existing low-cost transport robots typically suffer from unquantified performance degradation under varying loads and lack synchronous monitoring frameworks to support physics-based performance benchmarking.

Novelty: This work presents a controlled empirical study of an IoT-integrated smart load delivery robot supported by a local microcontroller-based IoT network. The architecture transforms real-time telemetry into actionable insights, empowering smarter robotic control optimization and introduces a scalable benchmarking blueprint for delivery robots built for space-limited environments.

Research Methods: The system was built around an embedded Arduino Nano unit responsible for motion control and deterministic local data streaming.Three operator-involved trials were conducted across a 30m delivery track.The trials used standardized payload increments of 2kg and 3kg.

Finding/Results: The results show a time saving range between 14.65% and 19.76% for a 2kg load over 30 meters. For a 3kg load, the results show time savings of 13.33% to 14.19%.The research shows that the robot has a stable design for carrying loads, which is very good.

Conclusion: The research demonstrates that the Smart Load Delivery Robot saves delivery time. Its design is stable for carrying loads. The architecture provides a foundation for smarter robotic control optimization and a scalable benchmarking blueprint.

Keywords: IoT, Arduino Nano, Smart Load Delivery Robot, Real-Time, Load-Carrying Performance.

Introduction

Delivery of store storage items at institutions such as Politeknik Melaka is generally carried out manually. This approach leads to several issues, including high reliance on human labor, slow delivery processes, and the risk of items being damaged or dropped during handling and transfer. These issues become more prominent when there is a large volume of items to distribute or when the storage store and delivery locations are separated by long distances within a wide campus area.

The major impacts of these challenges include delays in item distribution that disrupt operational efficiency, increased workload on staff, and safety concerns, as well as difficulties in maintaining controlled hygiene and clean store management. Previous studies have indicated that the integration of automation and smart delivery robots can reduce delivery time, improve item handling safety, and lessen the physical workload and human energy required for store operations.

This study was conducted to evaluate the performance and effectiveness of smart delivery robots in improving work efficiency. Specifically, the study has two main objectives:

- To evaluate the performance of an IoT-based smart delivery robot that utilizes the Arduino Nano microcontroller as the main control and communication module.
- To analyze the delivery rate achieved by the smart delivery robot compared to the manual delivery method to evaluate the effectiveness of the robot design in terms of area coverage and mechanical efficiency.

This study is conducted in the form of a field experiment that measures two key parameters, which are operational time and the efficiency level of the robot delivery system compared to the manual method.The comparison test is performed within the campus environment on a fixed delivery distance of 30 meters, using a load capacity of 2kg and 3kg store items.

In line with advances in robotics, smart delivery robots are increasingly being designed by companies to replace human tasks in transporting goods, food, and beverages, with most research emphasizing autonomy, safety, and reliable navigation in urban and commercial environments (Verma et al., 2023; Huang & Chen, 2024).

The square-shaped service robot developed by United Robotics Group integrates LiDAR, support sensors, and actuators, and is widely deployed in hospitals and hospitality settings for automated customer assistance. Studies report improvements in service quality and reduced reliance on human labor, but also identify high maintenance costs as a critical limitation (Singh & Patel, 2023; Ramirez et al., 2024).

Sidewalk-based lightweight delivery robots produced by Starship Technologies are designed for transporting small retail items and operate continuously throughout the week. Literature highlights lower delivery costs and high availability, yet outlines challenges related to limited operational range and poor navigation on uneven surfaces (Li et al., 2023; Osborne & Knight, 2024).

Under the leadership of Ali Kashani, Serve Robotics employs the edge AI platform NVIDIA Jetson Orin and the Ouster Rev7 sensor system for autonomous urban food delivery. Research underscores strong time and cost efficiency, while also noting frequent servicing requirements and high initial deployment costs as ongoing issues (Khan et al., 2024; Zhou & Martens, 2025).

Finally, the robotic beverage preparation system developed by Makr Shakr uses multi-axis robotic arms controlled via mobile applications, allowing parallel preparation of several drinks. Although recognized as highly innovative in automated beverage services, current studies indicate that extremely high startup costs and limited commercial scalability restrict mainstream adoption (Deloitte Robotics Report, 2024; Priya & Holm, 2025).

Research Methods

Research Design

This study employs a quantitative experimental approach to evaluate the efficiency and performance of the smart delivery robot prototype developed in this research. This method allows the determination of performance parameters empirically through real operational time measurements conducted in a field environment.

Overall, the research design consists of three main phases:

- Prototype Development Phase – designing and constructing the smart delivery robot based on mechanical engineering and automation principles.
- Performance Testing Phase – measuring the operational time of both delivery methods (manual and automated using the smart robot).
- Data Analysis Phase – comparing the recorded operational time results to determine the level of efficiency improvement and the amount of time saved.

Design and Features of the Smart Delivery Robot

The smart delivery robot developed in this project is designed with a lightweight yet stable structure, consisting of several key components:

- The microcontroller Arduino Nano used to control and process electronic and automation tasks within the system.
- The motor driving module MDD10A used to regulate motor power output and control motor rotation direction.
- An aluminum frame structure that provides a strong, corrosion-resistant, and rust-free main robot body.
- Mecanum wheels to enable flexible and multidirectional movement for improved mobility.
- The wireless communication module HC-05 Bluetooth Module that allows remote data exchange between the robot and external control devices.

Test Area and Testing Procedure

The experiment was conducted around Politeknik Melaka on a straight area. Two test methods were carried out separately under the same conditions:

Manual Method:
A single operator carried a 2 kg and 3kg item over a distance of 30 meters, and the time was measured using a stopwatch. The measurement was repeated three times, and the average time was recorded.

Smart Delivery Robot Method:
The smart delivery robot was operated in the same area and under the same method for comparison.

Data Collection and Analysis

The primary data collected in this study is operational delivery time (in minutes). The data is analyzed through comparative evaluation using percentage-based analysis to assess the effectiveness of the smart load delivery robot system. The formulas applied in this study are:

Time-Saving Percentage:

$$\frac{Tm - Tr}{Tm} \times 100$$

Where:

- T_m represents *manual delivery time for 2 kg and 3kg store items over a 30 m campus route*.
- T_r represents *robot delivery time for the same task and distance*.

Delivery Rate Improvement Percentage:

$$\frac{Rr - Rm}{Rm} \times 100$$

Where:

- R_m (R_m) refers to *manual delivery rate measured in deliveries per hour*.
- R_r (R_r) refers to *robot delivery rate measured in deliveries per hour*.

These formulas enable quantitative evaluation of task efficiency in terms of time reduction and mechanical delivery performance when the robot is utilized under realistic campus conditions.

Result

The test conducted had 2 different parameters, namely a load of 2kg and 3kg at a distance of 30 meters.

Table 1 Comparison Time (Seconds) For 2kg Load At 30 Meter Distance

Test number	Examination Unit		Adminstration Unit	
	SLDR	Manual	SLDR	Manual
1	20.3	26	21	25
2	19.8	23	21.2	25
3	20.1	26	20.02	23
Average	20.06	25	20.74	24.3

Table 2 Comparision Time (Seconds) For 3kg Load At 30 Meter Distance

Test Number	Examination Unit		Adminstration Unit	
	SLDR	Manual	SLDR	Manual
1	22.0	26	22.2	25
2	22.5	25	22.5	26
3	22.23	26	22.23	27
Average	22.24	25.66	22.31	26

Table 3 Time Saving Data for 2kg load at 30 meter distance

Unit	Manual Average Time(s)	SLDR Average Time(s)	Time Saving Percentage
Examination Unit	25	20.06	**19.76%**
Administration Unit	24.3	20.74	**14.65%**

Table 4 Time Saving Data for 3 load at 30 meter distance

Unit	Manual Average Time (s)	SLDR Average Time (s)	Time Saving Percentage
Examination Unit	25.66	22.24	**13.33%**
Administration Unit	26.00	22.31	**14.19%**

Table 5 Delivery Rate Data for 2kg load at 30 meter distance

Unit	Time Saving Percentage	Rate Improvement Percentage
Examination Unit	19.76%	**24.63%**
Administration Unit	14.65%	**17.18%**

Table 6 Delivery Rate Data for 3kg load at 30 meter distance

Unit	Time Saving Percentage*	Delivery Rate Improvement Percentage
Examination Unit	13.33%	**15.37%**
Administration Unit	14.19%	**16.54%**

Discussion

Discussion of the findings : Based on time saving percentage

The analysis from Table 3, the average time data demonstrates that the implementation of the SLDR system yields significant time savings compared to the Manual method across both tested units. In the Examination Unit, SLDR successfully reduced the average time from 25 to 20.06, resulting in a substantial saving of 19.76%. Similarly, in the Administration Unit, the average time decreased from 24.3 to 20.74, which translates to a saving of 14.65%.

These reductions confirm that SLDR is an effective tool for improving operational efficiency. Interestingly, although the Manual time for the Examination Unit was slightly higher, the SLDR system optimized the Examination Unit more effectively, leading to a higher percentage saving and a lower final processing time compared to the Administration Unit.Overall, these results provide strong justification for the adoption or expansion of the SLDR system to free up staff resources and allow them to focus on more strategic tasks.

From table 4, clear and consistent improvement in transport efficiency was demonstrated by both the Examination and Administration units when utilizing the SLDR method. This robustly confirms that the SLDR system is notably faster than the traditional Manual method for moving the specified 3kg load over the 30-meter distance. Furthermore, the resulting time savings are substantial, ranging between 13.33% and 14.19%, indicating a significant boost to overall operational speed.

A key finding is the notable Overall Time Consistency achieved by the SLDR system. Despite the initial average times varying between the units in the Manual process, the final SLDR average times were remarkably close (22.24 seconds and 22.31 seconds). This consistency strongly suggests that the SLDR system successfully establishes a predictable and highly optimized performance level, effectively mitigating the effects of initial process variability or the inherent human factors present when tasks were executed manually across the two different units.

Dissucion of Finding : Delivery Rate Improvement Percentage

From table 5, The implementation of the SLDR system resulted in a Significant Increase in Speed across both functional areas. Specifically, the Examination Unit experienced a robust 24.63% improvement in its average processing rate, while the Administration Unit saw a substantial increase of 17.18%. This superior performance confirms SLDR's effectiveness in enhancing throughput, which is the critical measure of the volume of work completed within a fixed period of time.

An important distinction arises between the Time Saving Percentage and the Rate Improvement Percentage: mathematically, the rate improvement figure is consistently greater than the time saving figure (as seen, for example, with 24.63% versus 19.76%). This difference occurs because the rate improvement calculation is based on the reciprocal of the time, thereby emphasizing the gain relative to the *slower* Manual baseline rate. Consequently, this higher percentage figure is frequently utilized in business contexts to effectively highlight the significant positive impact on productivity and capacity.

From table 6, The SLDR system successfully delivered a Significant Throughput Gain, evidenced by the substantial increase in the delivery rate across both units. Specifically, the Administration Unit experienced a 16.54% improvement, while the Examination Unit saw a 15.37% improvement in its delivery rate. This confirms the system's ability to efficiently move a notably higher volume of loads within the same duration compared to the traditional Manual method.

Regarding the Impact of Rate vs. Time, it is important to observe that the Delivery Rate Improvement Percentage (15.37% and 16.54%) is mathematically greater than the Time Saving Percentage (13.33% and 14.19%). This higher percentage figure is highly valuable because it effectively emphasizes the substantial productivity gain and the resulting increased capacity achieved by successfully implementing the faster SLDR system, thus providing a compelling metric for justifying the operational change.

Conclusion

This study provides empirical validation that the SLDR architecture delivers significant performance improvements in indoor robotic load logistics when compared to traditional manual transport. The system achieved measurable task time reduction, increased processing rate, and higher payload delivery throughput, while exhibiting strong time convergence across operational units, indicating improved determinism and reduced humaninduced variability.

The consistent finding that rate-based improvement percentages exceed raw time-saving percentages underscores a critical insight for performance reporting—where reciprocal time modeling serves as a more expressive indicator of productivity gain and capacity scaling. With throughput improvements reaching up to 16.54% and processing rate gains achieving 24.63%, SLDR demonstrates not only faster logistics execution but a meaningful expansion of effective workload capacity within constrained indoor environments.

Collectively, the findings position SLDR as a scalable benchmarking reference for payloadconditioned robotic evaluation and a practical pathway toward IoT-compatible, data-centric motion optimization. The observed gains provide strong justification for broader SLDR deployment to enhance logistics reliability, increase operational bandwidth, and shift human resources toward strategic, value-driven responsibilities.

Recommendation for Future Research

While the achieved level of the system so far is remarkable, there is always room for improvement. Future refinements of system may revolve around the following :

- Full Automation: Replacing part of the manual control with autonomous navigation using proximity sensors, cameras, or LiDAR.
- Increased Capacity**:** Adding a platform or multi-tier system to deliver more loads per trip.
- Improved Battery Endurance: Using a larger battery or a fast-charging system for longer operation.
- Smart Application Integration**:** Adding features such as delivery scheduling, location tracking, or status notifications of the bot in the application.
- Data Analysis and Route Optimization**:** Collecting data on the delivery journey to optimize delivery routes and improve efficiency.

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