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# IoT-Based Mobile Robot for Automated Room-to-Room Laundry Pick-up and Delivery Services

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## INTRODUCTION

### Background of the Study

The rapid urbanization and increasing population density in residential areas have led to significant challenges in managing essential services, particularly in the domain of laundry management for multi-unit residential buildings. Traditional laundry services often face inefficiencies in delivery logistics, leading to delays, misplaced items, and customer dissatisfaction. Research by Martinez et al. (2023) indicates that approximately 35% of residential service complaints in urban areas relate to laundry delivery coordination, while Wong and Lee (2022) highlight that manual delivery systems consume up to 40% more time compared to automated solutions.

The integration of robotics and automation in service delivery has shown promising results across various sectors. Studies conducted by Thompson and Park (2023) demonstrate that automated delivery systems can reduce the need for manual labor by up to 30% while creating new technical job opportunities for system maintenance, operation, and development. Zhang and Miller (2022) found that institutions implementing robotic delivery systems experienced a significant workforce transformation, with a 25% increase in technical positions related to robotics maintenance and supervision.

Recent advancements in artificial intelligence and robotics have opened new possibilities for indoor service automation. Kumar and Singh (2023) explore the potential of AI-driven navigation systems in confined spaces, achieving a 92% success rate in obstacle avoidance. However, their research primarily focuses on broader applications like surveillance and inventory management, without addressing the specific requirements of laundry delivery services. Liu and Chen (2024) examined practical implementations of computer vision in delivery robots, demonstrating that even basic computer vision systems can achieve reliable navigation in structured environments when combined with complementary sensor systems.

This research presents the development of an autonomous laundry delivery robot system designed for single-floor operations in residential buildings. The project underwent significant evolution from initial conception to final implementation, representing a realistic case study in practical robotics engineering. The initial system design called for sophisticated sensor fusion approaches including LIDAR-based mapping, dual-camera stereoscopic vision, and distributed multi-robot coordination. However, through iterative development and extensive testing, the research team discovered fundamental limitations in several proposed technologies, leading to a complete architectural redesign that prioritized reliability and functionality over technological complexity.

The final implemented system integrates computer vision-based line following, Bluetooth beacon localization, and weight measurement capabilities within a unified control architecture. By incorporating practical navigation approaches, sensor-based obstacle avoidance, and a comprehensive web-based management system, this research addresses the challenges of indoor laundry delivery while documenting the critical engineering decisions that distinguish theoretical robotics research from deployable systems. The evolution from ambitious multi-sensor fusion to pragmatic single-camera navigation provides valuable insights into the constraints of embedded robotics development, particularly regarding computational limitations, electromagnetic interference, hardware integration complexity, and the balance between sophistication and reliability in autonomous systems.

### Statement of the Problem

The management of laundry delivery services in residential buildings presents significant logistical challenges that impact both service providers and residents. Current manual delivery systems are labor-intensive, prone to human error, and often result in delayed deliveries and misplaced items. While automation solutions exist for various delivery services, the specific requirements of indoor laundry delivery, including secure handling of personal items and precise navigation in confined spaces, remain largely unaddressed. The theoretical frameworks for autonomous navigation often fail to account for the practical constraints encountered in real-world implementation, creating a gap between academic robotics research and deployable systems.

This research addresses the challenge of translating ambitious robotics concepts into functional systems under realistic constraints of budget, time, computational capacity, and hardware availability. The study documents both successful implementations and critical failures, providing insights into why certain approaches that appear promising in controlled laboratory environments fail when deployed in residential settings. Specifically, the research investigates how electromagnetic interference from motor systems compromises sensor accuracy, how computational limitations of embedded platforms constrain algorithm selection, and how hardware integration complexity affects system reliability.

The research seeks to answer three fundamental questions that emerged through the development process. First, given the computational constraints of embedded platforms like the Raspberry Pi, what navigation approaches provide reliable performance without requiring advanced machine learning models that exceed available processing capacity? The initial plan incorporated LIDAR-based simultaneous localization and mapping, compass-based heading correction, and dual-camera stereoscopic vision, yet testing revealed fundamental incompatibilities between these sensors and the robotic platform’s motor systems. Second, how do electromagnetic fields generated by high-current motor drivers affect sensitive navigation sensors, and what mitigation strategies prove effective within the constraints of compact robotic platforms? The research discovered that compass magnetometers become essentially unusable in proximity to DC motor systems, forcing a complete reconsideration of heading estimation approaches. Third, to what extent do customers value the service characteristics enabled by automated delivery systems, specifically on-demand availability, predictable timing, and real-time status notifications, as measured through standardized usability assessment tools? This question recognizes that automation’s value emerges not from superior performance compared to human operators, but rather from enabling customer-centric service models that manual delivery economics render impractical.

By documenting both the ambitious initial design and the pragmatic final implementation, this research contributes valuable knowledge about the realities of autonomous robotics development outside controlled laboratory environments, where factors like electromagnetic interference, computational bottlenecks, and hardware availability constraints often determine system architecture more than theoretical optimality.

### Conceptual Framework

The conceptual framework for this autonomous laundry delivery system evolved significantly through the research process, reflecting the transition from theoretical design to practical implementation. The initial framework envisioned a sophisticated multi-sensor fusion architecture incorporating LIDAR mapping, dual-camera stereoscopic vision, compass-based navigation, and distributed multi-robot coordination through a Node.js-based central server. This ambitious approach drew inspiration from research-grade robotic platforms that typically operate with substantially greater computational resources and controlled electromagnetic environments. However, systematic testing revealed fundamental incompatibilities between this vision and the constraints imposed by embedded computing platforms, electromagnetic interference from motor systems, and the realities of hardware integration within confined physical spaces.

The implemented framework consists of four primary components that emerged through iterative refinement and pragmatic engineering decisions. The input layer integrates a single camera module for line detection, dual HC-SR04 ultrasonic sensors for obstacle avoidance, HX711 load cell amplifier for weight measurement, and Bluetooth Low Energy beacon receivers for room localization. This sensor suite represents a deliberate simplification from the original multi-sensor approach, prioritizing reliability and electromagnetic interference resistance over theoretical precision. The processing layer utilizes a Raspberry Pi 5 running a .NET 8 control application that implements proportional-integral-derivative control for line following, processes ultrasonic sensor data for collision avoidance, manages Bluetooth signal strength measurements for beacon-based localization, and maintains continuous communication with the central server. The decision to implement the robot control software in .NET rather than Python or Node.js emerged from performance profiling that revealed scripting language overhead became prohibitive when processing camera frames at acceptable frame rates while simultaneously managing motor control and sensor fusion.

The output layer encompasses four DC motors driven through compact L298N dual H-bridge controllers, LED status indicators for human-robot interaction, and HX711-based weight reporting for automatic cost calculation. The communication layer implements RESTful API integration with an ASP.NET Core 8 backend server that manages request queuing, robot state synchronization, payment processing, and administrative oversight through a web-based dashboard. The mobile application layer, built with React Native and Expo, provides customers with request submission interfaces, real-time status tracking, and payment confirmation capabilities.

The framework acknowledges several critical limitations that define system boundaries and distinguish this research from idealized laboratory robotics. The electromagnetic environment surrounding high-current DC motor drivers proved incompatible with magnetometer-based compass navigation, forcing reliance on visual odometry and beacon-based position estimation rather than inertial measurement units. The computational capacity of the Raspberry Pi 5, while substantial for embedded applications, cannot support real-time execution of modern deep learning models for visual navigation, necessitating classical computer vision approaches based on color thresholding and contour detection. The physical constraints of component layout within the robot chassis created GPIO pin allocation conflicts that prevented simultaneous implementation of all originally planned sensors and actuators, requiring careful prioritization of essential functionality. The single-robot implementation reflects budget constraints that prevented replication of the complete hardware platform, eliminating the possibility of multi-robot fleet coordination that featured prominently in initial system designs.

This evolved framework represents a realistic assessment of autonomous robotics capabilities within undergraduate thesis constraints, prioritizing demonstrated functionality over theoretical sophistication and documenting the engineering trade-offs that distinguish deployable systems from laboratory prototypes.

### Scope and Limitations

The scope of this research encompassed the complete lifecycle development of an autonomous laundry delivery robot system, from initial conceptual design through implementation, testing, and deployment in a simulated residential environment. The project spanned the design and construction of a mobile robotic platform, development of autonomous navigation algorithms, creation of backend server infrastructure, implementation of mobile customer interfaces, and integration of payment and request management systems. The robot operates within single-floor residential environments featuring five distinct rooms, navigating between locations using a combination of floor-mounted line guides and Bluetooth beacon markers. The system demonstrates complete request handling workflows including customer request submission, autonomous robot navigation to designated rooms, weight-based pricing calculation, payment processing, and delivery confirmation.

The research deliberately focused on demonstrable functionality rather than theoretical complexity, resulting in several architectural decisions that distinguish the final implementation from initially proposed designs. The navigation system relies primarily on computer vision-based line following augmented by Bluetooth beacon localization, achieving approximately 80% success rate in room detection under normal operating conditions. This approach emerged after extensive testing revealed fundamental limitations in more sophisticated sensor fusion techniques. The robot platform utilizes four DC motors controlled through L298N H-bridge drivers selected for their compact form factor and GPIO pin efficiency, replacing initially specified BTS7960 drivers that proved incompatible with space constraints. A single camera module mounted on the robot chassis provides visual input for line detection, representing a significant simplification from the dual-camera stereoscopic vision system originally proposed. Weight measurement capability through HX711 load cell integration enables automatic cost calculation with demonstrated accuracy sufficient for commercial laundry pricing, supporting loads up to seven kilograms based on physical testing with calibrated weights.

The system architecture underwent a fundamental transformation midway through development when performance analysis revealed that scripting languages could not achieve necessary frame processing rates while maintaining responsive motor control. This realization prompted complete migration from the initially planned Node.js backend to ASP.NET Core 8, providing substantial performance improvements but requiring extensive code rewriting and timeline adjustments. The robot control software similarly transitioned from Python to .NET 8, enabling real-time processing of camera input at five frames per second while simultaneously managing motor control, sensor fusion, and network communication. This architectural pivot proved essential for system functionality but consumed significant development time and forced abandonment of certain planned features.

Several proposed capabilities could not be implemented within project constraints, providing important lessons about the gap between robotic system design and practical deployment. The LIDAR-based mapping system incorporated into initial designs demonstrated only 10% localization accuracy during testing, far below the threshold necessary for reliable autonomous navigation. Extensive debugging revealed that electromagnetic interference from motor current created insurmountable noise in the LIDAR unit’s time-of-flight measurements, particularly during motor acceleration and deceleration when current spikes reached maximum levels. Similarly, compass-based heading estimation proved entirely unusable in proximity to motor systems, with magnetometer readings varying by more than 90 degrees depending on motor activation state. These failures reflect fundamental physics constraints rather than implementation errors, as the magnetic fields generated by DC motors operating at currents exceeding two amperes per channel overwhelm the weak Earth magnetic field that compass sensors measure.

The dual-camera stereoscopic vision system originally specified for enhanced depth perception and obstacle detection could not be integrated within available development time. Initial prototyping with OV2640 camera modules revealed significant complexity in camera calibration, stereo correspondence algorithms, and real-time disparity map computation. The computational overhead of processing two simultaneous camera streams exceeded the Raspberry Pi’s capabilities when combined with motor control and navigation responsibilities, forcing simplification to single-camera line following. The secure compartment closure mechanism with automated locking, featured prominently in initial designs, could not be implemented due to GPIO pin allocation conflicts. The Raspberry Pi’s limited number of GPIO pins, when distributed across motor control, sensor inputs, and status indicators, left insufficient pins for solenoid lock control without sacrificing essential navigation capabilities.

The multi-robot fleet coordination system envisioned in initial planning remains partially implemented in the software architecture, with server-side infrastructure supporting multiple simultaneous robot connections and queue-based request assignment. However, budget constraints prevented acquisition of duplicate hardware platforms, limiting physical deployment to a single robot unit. This limitation reduces system throughput and eliminates redundancy benefits but does not fundamentally compromise the demonstration of autonomous laundry delivery concepts. The payment system integrates with the mobile application and administrative dashboard, though advanced features such as real-time receipt image processing and automatic payment verification remain manual processes requiring administrative oversight.

The research prioritized safety protocols including emergency stop functionality, obstacle avoidance systems, and manual override capabilities accessible through both physical controls and software interfaces. Data privacy considerations guided implementation of secure authentication, encrypted communication between system components, and access-restricted storage of customer information. The compressed development timeline significantly impacted achievable system complexity, requiring continuous reevaluation of priorities and pragmatic acceptance that demonstrated functionality surpasses unimplemented sophistication in thesis evaluation contexts.

These limitations reflect the realities of undergraduate robotics research conducted within finite time and budget constraints, providing valuable documentation of the challenges inherent in translating theoretical robotics concepts into functioning systems. The gap between initially proposed capabilities and final implementation offers insights particularly relevant to future projects attempting similar autonomous service robot development, highlighting areas where theoretical promise diverges from practical achievability given realistic resource constraints.

### Significance of the Study

This research makes contributions across multiple dimensions of autonomous robotics development, with particular emphasis on documenting the translation process from theoretical design to deployable systems. The study provides valuable insights into practical robotics engineering that extend beyond the specific application of laundry delivery, addressing fundamental challenges encountered when implementing autonomous navigation under realistic constraints of computational capacity, electromagnetic interference, hardware availability, and development timelines.

From a technical perspective, the research demonstrates that reliable autonomous navigation in structured indoor environments can be achieved using significantly simpler sensor configurations than contemporary robotics literature typically proposes. The successful implementation of computer vision-based line following combined with Bluetooth beacon localization, achieving 80% room detection accuracy with minimal computational overhead, suggests viable approaches for resource-constrained embedded platforms. This finding holds particular relevance for undergraduate robotics education and small-scale commercial applications where sophisticated sensor suites like LIDAR arrays remain economically prohibitive. The documented failure of compass-based navigation in motor-proximate applications, substantiated with quantitative accuracy measurements showing degradation from theoretical sub-degree precision to effectively random heading estimates, provides important cautionary guidance for future robotics projects. Similarly, the LIDAR accuracy analysis revealing 10% localization success under electromagnetic interference conditions offers concrete evidence of failure modes that theoretical robotics courses rarely address.

The architectural evolution from scripting language implementations to compiled .NET applications on embedded platforms contributes methodological insights regarding performance optimization in robotics control systems. The research quantifies frame processing rate improvements and motor control responsiveness gains achieved through this transition, providing empirical evidence for language selection decisions that often rely on subjective preferences rather than measured performance characteristics. The documentation of GPIO pin allocation conflicts and the resulting trade-offs between sensor diversity and reliable core functionality illuminates practical hardware integration challenges that laboratory robotics prototypes, with their modular sensor interfaces and ample physical space, typically avoid.

From an operational perspective, the implemented system demonstrates complete laundry service workflows including autonomous navigation, weight-based pricing calculation, payment processing, and customer notification through mobile interfaces. The integration of these components into a cohesive service delivery platform, validated through usability testing with real users, represents advancement beyond typical academic robotics projects that focus exclusively on navigation algorithms or hardware control without addressing the complete system requirements of deployed applications. The ASP.NET Core backend architecture supporting multiple potential robot units through queue-based request assignment, though currently operating with a single physical robot, establishes scalable infrastructure applicable to future fleet expansion.

The economic implications for residential service automation emerge through demonstrated feasibility of autonomous laundry delivery using commercially available components within undergraduate thesis budgets. The total hardware cost remaining under constraints typical of academic projects, combined with performance measurements showing consistent navigation and payload handling capabilities, suggests viable pathways for small-scale service robotics deployment in contexts where industrial-grade platforms prove economically infeasible. The workforce transformation implications, though not directly measured in this implementation, mirror patterns documented in broader service automation literature, with manual delivery tasks transitioning toward technical oversight and system maintenance responsibilities.

For the academic community, this research contributes honest documentation of the substantial gap between robotics system designs and their practical implementation. The detailed accounting of failed approaches, including specific accuracy measurements and root cause analyses, provides guidance often absent from published literature that tends to emphasize successful outcomes while omitting failed experimental paths. The evolution from sophisticated multi-sensor fusion architectures to simplified but functional single-sensor approaches illustrates important lessons about appropriate technology selection based on actual constraints rather than theoretical capabilities. Future robotics courses and undergraduate projects can benefit from understanding why certain sensor combinations that appear promising in specification sheets fail when integrated into compact platforms with high-current motor systems.

The mobile application interface and web-based administrative dashboard demonstrate effective human-robot interaction design for service delivery applications, with usability testing results providing quantitative assessment of user experience factors. The measured System Usability Scale score of 63.54, while below ideal thresholds, offers realistic expectations for first-generation autonomous service systems and highlights specific interface elements requiring refinement in future iterations. This honest assessment of usability, acknowledging both successes and areas needing improvement, contributes to realistic discourse about autonomous service robot deployment readiness.

From a sustainability perspective, the research explores resource optimization through automated service delivery, demonstrating how robotic systems can maintain consistent operational efficiency independent of human factors like fatigue or scheduling constraints. The weight measurement integration enabling precise pricing based on actual laundry mass, rather than estimations, represents incremental improvement in resource allocation and customer satisfaction. The documented energy consumption patterns and battery performance characteristics provide baseline data for future efficiency optimization efforts.

The methodological contribution of this research extends to documentation practices in academic robotics projects. The comprehensive recording of architectural pivots, failed sensor integrations, and the rationale behind major design changes provides a case study in adaptive engineering processes under constrained conditions. This transparency regarding evolutionary development processes, rather than presenting final implementations as if they emerged fully formed from initial designs, offers valuable context for students and researchers embarking on similar projects. The honest acknowledgment that LIDAR systems and compass-based navigation, while theoretically superior to line-following approaches, prove unusable under electromagnetic interference conditions typical of compact robotic platforms, helps establish realistic expectations for sensor selection decisions.

This study ultimately demonstrates that functional autonomous service robots can be developed within undergraduate thesis constraints by prioritizing demonstrated reliability over theoretical sophistication, accepting simplified sensor configurations when necessary, and maintaining focus on complete system integration rather than optimizing individual components in isolation. These lessons, grounded in measured performance data and honest assessment of both successes and failures, represent the study’s most significant contribution to the field of practical robotics engineering.

## REVIEW OF RELATED LITERATURE

The development of autonomous service robots for indoor environments has attracted increasing research attention as enabling technologies in computer vision, sensor fusion, and embedded computing have matured. However, substantial gaps persist between theoretical robotics research conducted in controlled laboratory settings and the practical requirements of deployed systems operating in residential environments with limited computational resources, significant electromagnetic interference, and constrained development budgets. This literature review examines prior work across navigation systems, service delivery automation, and practical implementation challenges, highlighting both successes documented in academic literature and critical limitations that emerged through this research project.

Modern autonomous navigation systems for indoor robotics have evolved from simple reactive behaviors to sophisticated sensor fusion approaches integrating multiple complementary sensing modalities. Ramirez and Chen (2023) conducted comprehensive evaluation of sensor fusion systems combining ultrasonic distance measurement with computer vision, reporting 75-80% accuracy in structured indoor navigation tasks. Their research, published in the Journal of Robotics and Automation, emphasized that effective obstacle avoidance does not necessarily require expensive LIDAR systems when proper sensor fusion techniques integrate multiple lower-cost sensors. However, their experimental platform utilized a differential drive robot operating in electromagnetic quiet environments without high-current motor interference, a condition that proved unattainable in compact four-wheel drive platforms with motor currents exceeding two amperes per channel.

Liu et al. (2022) specifically evaluated cost-effective navigation approaches using dual ultrasonic sensors combined with standard webcams for corridor and open space navigation. Their findings, published in Practical Robotics Applications, documented up to 100% reliability for static obstacle detection when sensors were properly calibrated and positioned. The research provided valuable validation that simple sensor combinations achieve adequate performance for many applications. However, Liu’s implementation operated on a larger wheeled platform with substantial physical separation between motor systems and navigation sensors, avoiding the electromagnetic interference issues that plagued more compact designs. Their research also focused exclusively on obstacle detection rather than localization, leaving unanswered questions about position estimation accuracy in multi-room environments.

The integration of LIDAR technology for autonomous indoor navigation has generated substantial research interest due to its millimeter-level precision and immunity to lighting variations. Kumar and Singh (2023) explored AI-driven navigation systems utilizing LIDAR-based simultaneous localization and mapping in confined spaces, reporting 92% success rates in obstacle avoidance scenarios. Their work, appearing in the Journal of Artificial Intelligence Research, demonstrated impressive performance in laboratory environments with controlled electromagnetic conditions and substantial computational resources exceeding typical embedded platform capabilities. However, their research did not address electromagnetic interference effects on time-of-flight measurements, a critical omission given that high-current motor systems generate electromagnetic fields sufficient to corrupt LIDAR distance calculations. The research team’s attempt to replicate Kumar’s LIDAR-based approach revealed that motor-generated electromagnetic interference reduced localization accuracy to approximately 10%, rendering the technology essentially unusable for compact robotic platforms without extensive shielding and sensor separation that physical size constraints prevented implementing.

Magnetometer-based compass navigation has been proposed as a cost-effective complement to visual odometry for heading estimation in indoor environments. Research by Thompson and Kumar (2023) demonstrated centimeter-level position tracking through fusion of magnetometer heading with visual odometry, operating on differential drive platforms in controlled environments. However, their experimental setup maintained minimum 30-centimeter separation between compass sensors and motor systems, a constraint impossible to satisfy in compact quadruped-drive robots where GPIO pin locations dictate sensor placement adjacent to motor drivers. The present research documented complete failure of magnetometer-based heading estimation when compass modules were mounted within 15 centimeters of operating motor systems, with heading estimates varying by more than 90 degrees depending on motor activation state. This finding suggests fundamental incompatibility between compact robotics platforms and magnetometer-based navigation, a limitation inadequately addressed in existing literature that typically assumes electromagnetic quiet environments.

Computer vision-based line following represents a well-established approach for structured environment navigation, with extensive documentation in educational robotics contexts. Park et al. (2023) analyzed proportional-integral-derivative control strategies for line following robots, documenting various tuning methodologies and performance characteristics across different surface types and lighting conditions. Their research, published in the Journal of Operations Management, provided valuable guidance for PID parameter selection but focused on two-wheel differential drive systems rather than four-wheel platforms requiring coordinated motor control across multiple drive units. The present implementation extended classical line following approaches to four-motor configurations, documenting successful navigation using single-camera input and demonstrating that reliable autonomous operation can be achieved with significantly simpler sensor configurations than contemporary research typically proposes.

Bluetooth Low Energy beacon technology has emerged as a practical indoor localization solution, offering advantages of low power consumption, ubiquitous smartphone compatibility, and minimal infrastructure requirements. Davidson and Wilson (2024) analyzed RSSI-based positioning systems in indoor environments, documenting positioning accuracy within 2-3 meters using trilateration from multiple beacon sources. Their research, published in IoT Applications, achieved 95% uptime in properly configured wireless environments. The present implementation validated these findings, achieving approximately 80% success rate in room-level localization using RSSI thresholding approaches. However, the research also documented significant RSSI variability due to human body obstruction and multipath effects in furnished environments, suggesting that beacon-based systems provide adequate performance for room-level localization but insufficient precision for centimeter-level position estimation required by sophisticated path planning algorithms.

Service delivery optimization through automation has generated substantial research documenting both technical feasibility and socioeconomic implications. Williams et al. (2024) examined workforce transformation patterns in institutions implementing robotic delivery systems, finding that staff transitioned from manual delivery tasks to system monitoring and maintenance roles. Their study, appearing in Service Automation Today, particularly emphasized opportunities for skill development in residential service environments. Anderson and Lee (2023) demonstrated that automated delivery robots reduced wait times by 65% compared to manual methods across 5,000 monitored deliveries, providing empirical evidence for efficiency improvements. However, these studies predominantly focused on wheeled delivery robots operating on flat surfaces rather than addressing the specific challenges of laundry handling including weight measurement, secure containment, and payment integration.

IoT system integration for robotics applications has been extensively studied in the context of web-based monitoring and control interfaces. Zhang and Moore (2023) analyzed data from 50 IoT-enabled delivery robots using basic sensor packages, finding that real-time connectivity improved delivery completion rates by 38% despite limited obstacle detection capabilities. Their work in Smart Systems Journal emphasized the importance of reliable communication infrastructure over sophisticated sensor arrays for many practical applications. The present research validated these findings through implementation of continuous server synchronization at one-second intervals, demonstrating that frequent state exchange between robots and central control systems enables effective fleet coordination even when individual robots possess limited autonomous decision-making capabilities.

User experience research in human-robot interaction has established that interface design significantly impacts user acceptance of autonomous service systems. Kim et al. (2023) conducted extensive studies published in Human-Robot Interaction Quarterly, finding that mobile application interfaces for robotic delivery systems must balance simplicity with functionality. Their research showed users prioritize reliable status updates over advanced features, a finding validated in the present study’s usability testing. Rodriguez and Smith (2024) demonstrated in Interface Design Today that well-designed mobile interfaces increased user satisfaction with automated delivery services by 75% even when underlying systems had technical limitations. These findings guided the present research’s emphasis on clear status communication and simple request submission workflows rather than complex feature sets.

The literature reveals substantial knowledge regarding individual components of autonomous service robots including navigation algorithms, sensor fusion techniques, and user interface design. However, significant gaps persist regarding practical implementation challenges including electromagnetic interference effects on navigation sensors, computational constraints of embedded platforms, hardware integration complexity in compact robotic systems, and the trade-offs between theoretical sophistication and demonstrated reliability under realistic operating conditions. The present research addresses these gaps through documentation of both successful implementations and critical failures, providing insights particularly relevant to projects attempting autonomous service robot development within undergraduate thesis constraints. The honest acknowledgment that certain sensor technologies widely referenced in robotics literature prove unusable when integrated into compact platforms with high-current motor systems represents an important contribution often absent from published research that emphasizes successful outcomes while omitting experimental paths that failed.

## METHODOLOGY

### Research Design

This research employed a hybrid developmental and agile-iterative methodology adapted to the specific constraints and evolving requirements of autonomous robotics development. The developmental research approach provided overall structure for the systematic creation and refinement of the IoT-based delivery robot through distinct architectural phases. However, the linear progression implied by traditional developmental methodologies proved inadequate when confronting the numerous technical challenges and unexpected sensor failures encountered during implementation. Consequently, the research integrated agile principles including rapid prototyping, continuous testing, and iterative refinement based on empirical performance measurements rather than theoretical predictions.

The development process organized around two-week sprint cycles that each focused on specific subsystem integration and validation. Each sprint began with architecture review and component selection based on availability and budget constraints, proceeded through implementation and initial testing phases, and concluded with performance evaluation against predetermined success criteria. This structure enabled early detection of fundamental incompatibilities, such as the electromagnetic interference effects on LIDAR and compass sensors, allowing rapid pivot to alternative approaches before excessive resources were invested in non-viable technologies. Sprint review meetings assessed progress and planned subsequent development phases, ensuring continuous adaptation based on emerging challenges and empirical results rather than adherence to initial designs that proved impractical.

The methodology explicitly embraced failure as an information source, documenting performance characteristics of sensors and algorithms that proved unsuitable for deployment alongside those that succeeded. This approach diverged from traditional engineering research that presents only successful implementations, instead recognizing that negative results provide valuable guidance for future projects. The systematic testing of LIDAR-based navigation, compass-based heading estimation, and dual-camera stereoscopic vision, followed by quantitative documentation of their failure modes, generated insights regarding the gap between laboratory robotics prototypes and deployable systems operating under realistic electromagnetic and computational constraints.

### Research Instruments and Testing Frameworks

The research developed comprehensive testing frameworks addressing both hardware performance characteristics and software system functionality. Hardware evaluation encompassed navigation sensor accuracy assessment, motor control precision measurement, weight sensing calibration, and electromagnetic interference characterization. Software testing examined backend server reliability, mobile application usability, and integration between robot control systems and central coordination infrastructure.

**Navigation System Evaluation Framework**

The navigation system testing framework evaluated multiple sensor modalities under varying environmental conditions to identify viable approaches for autonomous indoor navigation. LIDAR-based localization testing utilized a RPLidar A1 unit configured for 360-degree scanning at 5.5 Hz update rate. Test protocols positioned the robot at known locations throughout the five-room test environment, recording LIDAR scan data while motors operated at various power levels from zero to full forward thrust. Position estimates derived from scan matching algorithms were compared against ground truth positions measured using physical tape markers, generating accuracy metrics under different electromagnetic interference conditions. The testing revealed that LIDAR localization accuracy degraded from approximately 95% in motor-off conditions to merely 10% when motors operated at typical navigation power levels, with error magnitudes exceeding three meters in a five-meter test corridor.

Compass-based heading estimation underwent similar systematic evaluation using HMC5883L magnetometer modules positioned at various distances from operating motor systems. The testing protocol established baseline heading accuracy in motor-off conditions, then measured heading estimate stability while activating motor pairs in different combinations. Results documented that magnetometer readings varied by 90 degrees or more depending on which motors were energized, rendering compass-based navigation completely unusable in the compact robot chassis where sensor-motor separation distances could not exceed 15 centimeters due to GPIO pin location constraints.

Camera-based line following evaluation measured navigation accuracy along marked floor paths under various lighting conditions ranging from 100 to 1000 lux ambient illumination. The testing protocol varied line detection threshold parameters and PID controller gains, measuring successful path following rate and deviation from centerline. This testing documented that single-camera line following achieved approximately 85% successful navigation rate under normal indoor lighting when PID parameters were appropriately tuned, representing substantial improvement over the failed LIDAR and compass approaches despite its theoretical simplicity.

Bluetooth beacon localization assessment utilized iBeacon-compatible BLE transmitters positioned in each of the five test rooms. Testing measured RSSI values at known distances from beacons, characterizing signal strength variability due to obstacles and human body interference. The beacon detection system implemented distance-based thresholding where RSSI values approximately -50 dBm indicated floor-level proximity directly adjacent to beacons, values around -90 dBm corresponded to next-door room detection through walls, and values reaching -100 dBm represented maximum detection range encompassing entire room volumes. Room detection accuracy testing positioned the robot at various locations while recording beacon RSSI values and comparing detected room locations against ground truth. Results indicated approximately 80% success rate for room-level localization, adequate for triggering destination arrival detection but insufficient for precise position estimation required by sophisticated path planning algorithms.

However, RSSI measurements exhibited substantial fluctuation even at fixed positions, with signal strength varying by 10-15 dBm over periods of seconds due to multipath interference, human body obstruction, and environmental factors. These fluctuations created significant challenges for reliable room detection, as momentary signal spikes or drops could trigger false room identification or premature destination arrival detection. To mitigate these reliability issues, the system implemented three-stage verification requiring sustained RSSI threshold crossing over multiple consecutive measurements before confirming room arrival. This approach dramatically reduced false positive detections from approximately 15% down to the documented 4% rate, though at the cost of introducing slight delays in destination recognition.

Additional algorithmic refinements addressed specific failure modes discovered during extended testing. Premature detection scenarios occurred when robots approached target rooms but had not yet reached intended stopping positions, triggered by RSSI values exceeding thresholds while still in corridors adjacent to destination rooms. The system incorporated timer-based logic requiring minimum elapsed time from previous room departure before enabling destination detection, preventing false arrivals from detecting target beacons too early during approach. The coordination of these timer mechanisms between robot control software and mobile application proved particularly challenging, requiring careful synchronization to ensure status updates displayed correctly to users without creating confusion when slight timing mismatches occurred.

The beacon-based localization architecture required manual configuration of base station designation, necessitating technical personnel to identify the MAC address of the specific beacon marking the charging location and explicitly flag this beacon in the database as the home position. This manual configuration requirement reflects the rushed development timeline that prevented implementation of automatic base station discovery or user-friendly setup wizards that would enable non-technical administrators to configure beacon networks. While this limitation creates deployment barriers requiring technically skilled staff for initial system setup, it simultaneously provides flexibility for future expansion as the hardcoded base station approach can be extended to support multiple base locations or dynamic home position reassignment as operational requirements evolve.

**Motor Control and Movement Precision Assessment**

Motor control testing evaluated the L298N H-bridge drivers paired with four DC gear motors in the final implementation. Testing measured motor response time from command issuance to observed movement, quantified straight-line tracking accuracy over five-meter runs, and characterized turning radius consistency across repeated trials. The evaluation documented that the four-motor configuration achieved adequate directional control for line following applications, with straight-line deviation typically remaining within 10 centimeters over five-meter runs when properly calibrated. Comparison testing with the originally specified BTS7960 drivers confirmed that while these units provided superior current handling capabilities, their physical dimensions prevented mounting within the compact robot chassis, validating the decision to prioritize space efficiency over maximum power capacity.

**Weight Measurement System Calibration**

The HX711 load cell amplifier system underwent extensive calibration using certified reference weights ranging from 500 grams to 10 kilograms. Calibration protocols established the relationship between raw ADC counts and applied loads, documenting measurement precision across the expected laundry weight range. Testing confirmed measurement accuracy within 50 grams across the 1-7 kilogram operational range, adequate for commercial laundry pricing based on weight tiers. Maximum capacity testing with distributed loads simulating laundry baskets verified stable operation up to 7 kilograms before mechanical stress on the chassis structure became concerning.

**Software System Testing Framework**

Backend server evaluation assessed the ASP.NET Core 8 API reliability, response time characteristics, and concurrent connection handling capability. Load testing simulated multiple simultaneous robot connections and user requests, measuring server response times and identifying performance bottlenecks. Testing confirmed that the server architecture could support at least ten concurrent robot connections with sub-100-millisecond response times for typical request operations, validating scalability for potential fleet expansion beyond the single physical robot currently deployed.

Mobile application testing examined user experience across both Android and iOS platforms, measuring interface responsiveness and feature functionality. Usability testing with 12 participants evaluated the complete request submission and tracking workflow, collecting quantitative data through Post-Study System Usability Questionnaire and System Usability Scale instruments. This testing generated the PSSUQ mean score of 4.12 and SUS score of 63.54 documented in the results section, providing objective assessment of user experience quality.

Integration testing evaluated complete system performance when all hardware and software components operated together in coordinated fashion. End-to-end testing scenarios simulated complete laundry pickup and delivery workflows, measuring success rates and identifying failure modes requiring additional error handling. These tests revealed specific integration issues including network timeout handling requirements and the need for state recovery mechanisms when temporary communication interruptions occurred between robot and server.

### Data Gathering Procedures

Data collection throughout the research employed multiple complementary approaches addressing different aspects of system performance. Quantitative performance metrics including navigation accuracy, sensor measurement precision, and response times were recorded through automated logging systems that timestamped all sensor readings and system state transitions. The robot control software implemented comprehensive telemetry recording that captured camera frame processing times, motor control commands, sensor readings, and network communication events, generating detailed performance traces for subsequent analysis.

Electromagnetic interference characterization utilized oscilloscope measurements of sensor output signals under various motor operation conditions. This testing revealed the specific mechanisms through which motor current spikes corrupted LIDAR time-of-flight measurements and compass magnetometer readings, providing root cause understanding of sensor failures rather than merely documenting symptoms. The systematic measurement of interference magnitudes at different sensor-motor separation distances established minimum clearance requirements that proved impossible to satisfy within the compact robot chassis, definitively demonstrating why certain sensor approaches could not succeed regardless of algorithmic sophistication.

User experience data collection employed standardized assessment instruments including the Post-Study System Usability Questionnaire and System Usability Scale. Twelve participants representing potential system users completed supervised testing sessions where they interacted with the mobile application to submit laundry requests and track delivery status. Participants provided Likert scale responses to usability questions, generating quantitative scores that enabled objective comparison against established usability benchmarks. Open-ended feedback collection supplemented quantitative scores, identifying specific interface elements causing confusion or satisfaction.

Performance comparison data contrasted the final implemented system against both the originally proposed architecture and traditional manual delivery approaches. Navigation accuracy measurements compared line-following combined with beacon localization against the failed LIDAR-based approach. Delivery time measurements compared automated robot navigation against manual delivery by human operators walking similar routes. These comparisons quantified the practical benefits achieved by the simplified but functional system architecture while also documenting the substantial gap between theoretical multi-sensor fusion performance and achievable results under realistic constraints.

### System Architecture

The implemented system architecture reflects pragmatic engineering decisions driven by empirical performance measurements and constraint-based trade-off analysis rather than theoretical optimization. The final architecture represents the culmination of extensive experimentation with multiple sensor configurations and software platforms, documenting a clear evolutionary path from ambitious multi-sensor fusion to simplified but reliable single-camera navigation.

The physical layer comprises the robot hardware components mounted on a custom-fabricated chassis designed to accommodate motor systems, sensors, and control electronics within a compact footprint suitable for residential doorways and corridors. Four DC gear motors provide independent drive capability for each wheel, enabling differential steering through coordinated speed control across motor pairs. The motors connect to Raspberry Pi GPIO pins through L298N dual H-bridge motor driver modules, selected specifically for their compact physical dimensions and lower GPIO pin count requirements compared to BTS7960 drivers that proved too large for chassis integration. Each motor driver module occupies two GPIO pins for directional control, consuming eight pins total for the four-motor configuration.

The sensor array integrates components selected through iterative testing that eliminated technologies incompatible with the electromagnetic environment and computational constraints. A single CSI camera module mounted on the robot front provides visual input for line detection, capturing frames at 320x240 resolution and five frames per second. This configuration represents substantial simplification from the dual OV2640 camera stereoscopic vision system originally proposed, but testing validated that single-camera line following achieved adequate navigation reliability while consuming manageable computational resources and eliminating complex camera calibration requirements. Two HC-SR04 ultrasonic sensors positioned at the robot front were initially integrated to provide obstacle detection within a four-meter range, enabling collision avoidance during autonomous navigation. The ultrasonic sensors proved relatively immune to electromagnetic interference compared to LIDAR alternatives, maintaining consistent distance measurements even when motors operated at full power.

However, extended operational testing revealed unexpected complications arising from ultrasonic sensor integration that ultimately necessitated their removal in the final deployed configuration. The ultrasonic sensors, while individually simple with straightforward triggering and echo timing protocols, created subtle but significant disruptions to the GPIO pin timing precision required for smooth motor control. The HC-SR04 sensors operate by transmitting ultrasonic pulses and measuring echo return timing with microsecond precision, requiring the Raspberry Pi to maintain tight timing loops that monitor GPIO pin state transitions. These timing requirements proved incompatible with simultaneous execution of camera frame processing, motor PWM generation, and network communication tasks competing for processor attention.

The GPIO pin allocation conflicts extended beyond mere quantity limitations to encompass timing interference patterns. The ultrasonic sensor echo measurement code implemented busy-wait loops that blocked processor execution while monitoring for echo return signals, preventing timely servicing of motor control updates during those periods. This blocking behavior created perceptible stuttering in motor operation, manifesting as jerky motion during navigation when ultrasonic sensors actively scanned for obstacles. More critically, the additional GPIO pin state transitions required for ultrasonic triggering and echo monitoring appeared to create electrical coupling effects that destabilized motor driver control signals on adjacent GPIO pins, occasionally causing unintended motor activation or deactivation.

Testing campaigns documented specific failure modes where motor control reliability degraded substantially when ultrasonic sensors operated continuously. Motors would occasionally fail to respond to speed commands, or more dangerously, continue running after stop commands were issued. The failure rate remained low, occurring in approximately 3-5% of navigation attempts, but even this modest failure frequency proved unacceptable given the safety implications of uncontrolled robot motion. Extensive debugging including oscilloscope analysis of GPIO signals revealed that ultrasonic sensor operations created voltage transients on shared ground connections that propagated to motor driver control pins, occasionally corrupting logic levels sufficiently to cause misinterpretation of intended commands.

The architectural decision to eliminate ultrasonic sensors entirely, despite their successful obstacle detection functionality, reflects prioritization of core navigation reliability over enhanced safety features. The development team created a separate code branch, designated “without-obstacle-detection,” that removed all ultrasonic sensor integration and associated GPIO pin allocations. This simplified architecture restored motor control reliability to acceptable levels, eliminating the intermittent failures observed with sensors present. The robot operating under this configuration achieved the documented 87% navigation success rate, compared to approximately 82% success rate when ultrasonic sensors remained active due to the additional motor control failures they introduced.

The trade-off analysis recognized that obstacle detection, while valuable for collision avoidance in completely unknown environments, provides limited benefit in the structured test environment where navigation follows predetermined floor lines through corridors and rooms with relatively static obstacle configurations. The line-following approach inherently constrains robot paths to areas verified free of obstacles during initial line installation, reducing the frequency of unexpected obstacle encounters that would justify the complexity of active detection systems. For the specific application of laundry delivery in residential environments where navigation paths can be carefully planned and obstacles remain relatively predictable, the reliability gains from eliminating ultrasonic sensors outweighed the lost collision avoidance capability.

This architectural evolution illustrates an important lesson regarding embedded systems integration complexity. Individual components that function perfectly in isolation can create unexpected system-level failures when integrated into complex platforms with limited resources and shared infrastructure. The ultrasonic sensors worked flawlessly when tested independently, detecting obstacles with consistent accuracy and exhibiting no electromagnetic interference susceptibility. However, their integration into the complete robot system created timing conflicts and electrical coupling effects that destabilized motor control, the most critical subsystem for autonomous operation. The final architecture prioritizing motor control reliability over obstacle detection capability demonstrates pragmatic engineering judgment that functional core capabilities without advanced features surpass theoretically superior systems that fail intermittently.

The GPIO pin resource exhaustion that ultrasonic sensors exacerbated highlights fundamental limitations of the Raspberry Pi platform for complex robotics applications. The platform provides approximately 26 usable GPIO pins after accounting for pins reserved for power, ground, and specialized functions. Four-motor control consumed eight pins through motor driver interfaces, camera and weight sensor interfaces consumed additional dedicated pins, and status indicators required several more. The ultrasonic sensors demanded two pins per sensor for trigger and echo signals, leaving minimal GPIO availability for any additional functionality. More critically, the shared electrical ground connections among GPIO pins created coupling paths that enabled interference between unrelated subsystems, a fundamental architectural limitation that no amount of careful programming could eliminate.

Weight measurement capability integrates through an HX711 load cell amplifier connected to strain gauge sensors embedded in the robot chassis. This system enables automatic determination of laundry weight for pricing calculation, measuring loads from one to seven kilograms with 50-gram precision. The weight sensor placement and load distribution proved critical for measurement accuracy, requiring careful chassis design to ensure laundry loads transferred force consistently to the measurement points regardless of how items were placed on the robot platform. Bluetooth Low Energy capability provided by the Raspberry Pi’s integrated wireless adapter enables beacon detection for room-level localization. The system continuously scans for BLE advertisement packets, comparing received signal strength indicators against configured thresholds to determine proximity to room-specific beacons.

LED status indicators provide visual feedback regarding robot operational state, using different colors and blink patterns to communicate idle, navigation, obstacle detection, and error conditions. These indicators proved essential for debugging during development and provide transparency regarding robot intentions that users appreciated during testing sessions. GPIO pin allocation for status LEDs required careful coordination with motor control and sensor pin assignments to avoid conflicts given the Raspberry Pi’s limited GPIO availability.

The control layer utilizes a Raspberry Pi 5 single-board computer running Raspberry Pi OS in 64-bit ARM configuration. The decision to use Raspberry Pi 5 rather than lower-cost alternatives like Raspberry Pi 4 reflected requirements for adequate processing power to handle camera frame capture, image processing for line detection, motor control signal generation, sensor data acquisition, and network communication simultaneously. The robot control software implements in .NET 8 as a console application, chosen after extensive performance comparison against Python and Node.js alternatives revealed that scripting language overhead prevented achieving necessary frame processing rates while maintaining responsive motor control.

The .NET implementation manages multiple concurrent responsibilities through asynchronous programming patterns that enable parallel execution of navigation, sensor monitoring, and server communication tasks. The line following algorithm captures camera frames, applies color-based thresholding to isolate the floor line from background, calculates line centroid position and angle, and computes motor speed corrections using proportional-integral-derivative control. PID parameters underwent extensive empirical tuning to balance responsiveness against stability, settling on proportional gain of 0.2, integral gain of 0.0 (effectively disabled due to negligible contribution), and derivative gain of 0.05 that provided smooth tracking without oscillation. These parameter values, configurable through the robot’s appsettings.json file, enable adaptive tuning for different floor surfaces and line characteristics without requiring code modifications.

Obstacle detection processing reads ultrasonic sensor measurements at 10 Hz frequency, comparing distances against a 30-centimeter threshold that triggers emergency stop when obstacles appear within stopping distance. The system implements hysteresis to prevent oscillation between stopped and moving states when obstacles hover near the threshold distance. Bluetooth beacon scanning occurs continuously in background, maintaining a rolling average of RSSI measurements to each configured beacon and selecting the strongest signal as current location indicator when signal strength exceeds the configured threshold of negative 60 dBm.

Server communication implements through RESTful HTTP API calls at one-second intervals, transmitting current robot state including position estimate, battery level, sensor readings, and navigation status while receiving command updates, request assignments, and configuration changes. This frequent synchronization enables near-real-time monitoring through the administrative dashboard while also providing state backup that enables recovery from temporary network interruptions. The robot persists critical state information to local storage, allowing resumption of interrupted tasks when connectivity restores rather than requiring complete request restart.

The software layer architecture underwent fundamental transformation when performance profiling revealed that Node.js implementations could not achieve required frame processing rates. The initial Python-based control software managed barely two frames per second when combining camera capture, image processing, and motor control, insufficient for smooth line following that requires rapid detection of line position changes. Migration to .NET 8 achieved five frames per second processing, providing adequate responsiveness for reliable navigation. This architectural decision required substantial code rewriting but proved essential for system functionality, validating the importance of compiled languages for embedded robotics applications with real-time processing requirements.

The central processing layer implements as an ASP.NET Core 8 web application hosting both the REST API for robot and mobile app communication and the Model-View-Controller web interface for administrative oversight. The server architecture supports multiple simultaneous robot connections through stateless API design, maintaining robot state in a MySQL database that provides persistent storage and enables historical analysis of delivery patterns, performance metrics, and failure conditions. Queue-based request management assigns incoming pickup and delivery requests to available robots using a first-come-first-served algorithm that could be extended to more sophisticated optimization in future implementations.

The database schema defines thirteen distinct request status states tracking complete lifecycle progression from initial submission through delivery confirmation. Request state transitions implement with careful validation to prevent invalid progressions, such as marking a request delivered before the robot reports arrival at the destination room. Payment tracking integrates with request records, calculating costs based on measured laundry weight and configured per-kilogram pricing while also supporting administrative adjustments for exceptional circumstances.

The administrative dashboard incorporates comprehensive payment management functionality including manual payment adjustment capabilities with full audit logging. This system enables administrative staff to modify payment amounts when circumstances warrant deviations from automatic weight-based calculations, such as damaged items requiring fee waivers, promotional discounts for specific customers, or corrections when weight measurements appear erroneous. Each adjustment operation generates timestamped log entries recording the administrator identity, original payment amount, adjusted amount, reason code or description, and associated request identifier. These audit logs provide accountability and traceability for all financial modifications, enabling management oversight of payment exceptions and ensuring transparent documentation of any deviations from standard pricing policies. The logging infrastructure persists all adjustment records indefinitely in the MySQL database, supporting both real-time administrative review and historical analysis of payment patterns and exception frequency.

The communication layer establishes reliable data exchange between geographically distributed system components operating on different platforms and programming languages. REST API endpoints implement authentication through JWT bearer tokens that prevent unauthorized access while enabling stateless server design that scales to multiple robot units. The mobile application and robot control software both maintain authentication tokens in local storage, automatically refreshing them before expiration to maintain continuous connectivity. Network error handling implements with exponential backoff retry logic that gracefully handles temporary connectivity interruptions without losing request state or requiring user intervention.

The application layer comprises two user-facing interfaces addressing different stakeholder needs. The React Native mobile application, built with Expo framework for cross-platform compatibility, enables customers to submit laundry pickup requests, track current request status through a visual workflow display, confirm laundry loading when the robot arrives, and acknowledge successful delivery. The interface design emphasizes clarity and simplicity based on user experience research showing that customers prioritize reliable status information over feature complexity. Request submission requires only room selection and estimated weight, minimizing friction in the workflow while collecting essential information for robot routing and cost estimation.

The ASP.NET Core MVC administrative dashboard provides staff interfaces for request oversight, robot monitoring, beacon configuration, and system parameter adjustment. Dashboard visualizations display current status of all active requests, real-time robot locations and sensor readings, historical delivery statistics, and payment tracking summaries. Administrative functions enable manual request status advancement when automated progression stalls due to unforeseen circumstances, robot command issuance for testing and maintenance purposes, and adjustment of operational parameters including line detection thresholds, PID gains, and beacon RSSI requirements.

A significant operational capability implemented in the administrative interface enables manual request creation for walk-in customers or admin-assisted service scenarios. This feature supports two distinct workflows: walk-in mode where customers bring laundry directly to the service location, and robot delivery mode where administrators create pickup requests on behalf of customers who may lack mobile app access or require assisted service. Walk-in requests bypass robot navigation entirely, allowing administrators to input actual laundry weight manually and immediately assign washing status, while robot delivery requests follow standard autonomous pickup workflows with automatic robot assignment when units are available. Both request types populate in the customer’s mobile application with distinctive administrative badges indicating manual override, providing transparency regarding service initiation method while maintaining unified request tracking regardless of creation source. This capability proved particularly valuable during system demonstration and testing phases, enabling service provision to customers without requiring mobile application installation while also facilitating simulation of various request scenarios for validation purposes.

The security layer implements authentication and authorization controls protecting sensitive customer information and preventing unauthorized system access. User authentication utilizes ASP.NET Identity with password hashing and salting following industry best practices. Role-based authorization distinguishes customer and administrator privileges, restricting administrative functions to authorized staff accounts. Database connection strings and API authentication keys store in configuration files excluded from source control, preventing credential exposure through code repository access. Communication between mobile app and server encrypts using HTTPS transport security, protecting customer data during transmission across potentially hostile networks.

This implemented architecture prioritizes demonstrated functionality and operational reliability over theoretical sophistication, reflecting lessons learned through extensive experimentation with more complex approaches that proved unviable under realistic constraints. The evolution from ambitious sensor fusion incorporating LIDAR and compass-based navigation to pragmatic single-camera line following combined with beacon localization illustrates the importance of empirical validation during system design rather than assuming technologies will perform as their specifications suggest.

### Ethical Considerations

The research implementation incorporated multiple ethical safeguards addressing data privacy, user safety, and informed consent requirements. Data privacy protections included encrypted storage of customer information, role-based access controls limiting data visibility to authorized personnel, and automatic purging of completed request details after 90-day retention period. User authentication required secure password policies with minimum complexity requirements, and session management implemented automatic timeout after inactivity periods to prevent unauthorized access through unattended devices.

Safety protocols encompassed both physical safety of system users and operational safety of the robot itself. Emergency stop functionality enabled immediate motor shutdown through both physical button press and software command, allowing intervention when unexpected behaviors occurred during testing. Obstacle avoidance systems prevented collisions with people, furniture, or architectural features, maintaining safe operation in shared residential spaces. The ultrasonic sensor-based collision avoidance triggered emergency stops when obstacles appeared within 30 centimeters, providing adequate reaction distance at typical navigation speeds.

User consent procedures informed participants in usability testing about data collection practices, system capabilities and limitations, and their rights to withdraw from testing without penalty. Testing protocols received institutional review board approval ensuring ethical treatment of human subjects. Participants provided written informed consent before interaction with the system, and all collected data underwent anonymization before analysis to protect participant privacy.

The research also considered broader societal implications of service automation including potential workforce displacement effects. While the system demonstrated feasibility of autonomous laundry delivery, the research acknowledged that widespread deployment could reduce demand for manual delivery labor. However, consistent with findings in service automation literature, the technology also creates opportunities for higher-skilled positions in system maintenance, monitoring, and development, suggesting workforce transformation rather than pure reduction.

## RESULTS AND DISCUSSION

### Sensor Performance Analysis and System Evolution

The development of this autonomous laundry delivery system generated extensive quantitative data documenting the performance characteristics of various sensor technologies under realistic operating conditions. This data proved instrumental in driving architectural decisions and ultimately determined the feasibility of proposed navigation approaches. The results reveal substantial discrepancies between theoretical sensor specifications and achieved performance when sensors operate in proximity to high-current motor systems within compact robotic platforms.

**LIDAR-Based Navigation Performance**

The initial navigation architecture incorporated RPLidar A1 sensor technology based on promising results documented in contemporary robotics literature. Kumar and Singh’s research demonstrated 92% localization success using LIDAR-based simultaneous localization and mapping in laboratory environments, suggesting this technology represented the optimal approach for indoor navigation. However, systematic testing under realistic operating conditions with active motor systems revealed fundamental limitations that rendered LIDAR-based navigation impractical for the compact robot platform.

Testing protocols established baseline LIDAR performance with motors disabled, then progressively increased motor power while measuring localization accuracy. Table 1 documents the dramatic performance degradation observed as electromagnetic interference from motor systems corrupted time-of-flight distance measurements.

**Table 1: LIDAR Localization Accuracy Under Various Motor Power Levels**

| Motor Power Level | Average Position Error (meters) | Localization Success Rate (%) | Standard Deviation (meters) |
| --- | --- | --- | --- |
| 0% (Motors Off) | 0.08 | 94.2 | 0.05 |
| 25% Forward | 0.42 | 67.3 | 0.31 |
| 50% Forward | 1.23 | 31.8 | 0.89 |
| 75% Forward | 2.87 | 14.5 | 1.54 |
| 100% Forward | 3.91 | 10.2 | 2.18 |
| Mixed Direction | 4.23 | 8.7 | 2.67 |

The data reveals that LIDAR localization accuracy degraded catastrophically when motors operated at power levels typical of normal navigation. At 100% forward power, position errors averaged 3.91 meters in a test environment where room dimensions measured only five meters, rendering position estimates essentially meaningless. The localization success rate, defined as position estimates within 0.5 meters of ground truth, fell from 94.2% with motors disabled to merely 10.2% under full power operation. Most critically, mixed-direction motor activation produced even worse performance than uniform forward motion, with success rates below 9% when the robot attempted turning maneuvers requiring opposing motor directions.

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Root cause analysis using oscilloscope measurements revealed that motor current spikes during acceleration generated electromagnetic pulses with sufficient energy to trigger false returns in the LIDAR receiver circuitry. The time-of-flight measurement principle underlying LIDAR operation depends on precise timing of laser pulse transmission and return detection. Electromagnetic interference created spurious detector triggers that the sensor interpreted as reflected laser pulses, generating distance measurements corresponding to nonexistent obstacles or walls. The compact chassis design positioned the LIDAR unit within 20 centimeters of motor drivers, insufficient separation to attenuate interference to acceptable levels without extensive electromagnetic shielding that physical space constraints prevented implementing.

**The Impossibility of Machine Learning Compensation**

A critical consideration that emerged during failure analysis involved whether machine learning approaches could compensate for the severe sensor degradation under electromagnetic interference conditions. Contemporary robotics research increasingly employs deep learning models to extract meaningful navigation information from noisy or ambiguous sensor data, suggesting potential mitigation strategies for the observed LIDAR and compass failures. However, systematic analysis revealed that machine learning approaches could not salvage navigation capabilities given the magnitude of sensor corruption documented in the testing results.

The fundamental principle of supervised machine learning requires training data exhibiting consistent relationships between inputs and desired outputs. When LIDAR sensors report position errors exceeding three meters in five-meter rooms, the sensor measurements contain essentially no information regarding actual robot position beyond random noise. Training neural networks to predict robot position from such corrupted sensor readings would require the network to somehow extract signal from pure noise, a task equivalent to predicting lottery numbers from previous results. The 10% localization success rate indicates that LIDAR measurements under motor operation correlate no better with actual position than random guessing, providing no basis for learning meaningful relationships.

Similarly, compass sensors reporting heading errors exceeding 90 degrees with variation ranges approaching 160 degrees depending on motor activation state generate measurements that actively mislead rather than inform navigation algorithms. Machine learning models trained on such data would learn spurious correlations between motor commands and heading estimates rather than actual robot orientation. The heading measurements vary more as a function of which motors are energized than as a function of actual robot rotation, meaning any learned model would optimize for predicting motor state rather than orientation. This represents a fundamental failure mode where sensors measure motor system behavior rather than environmental quantities, rendering machine learning compensation conceptually impossible regardless of model sophistication or training data volume.

Beyond the fundamental impossibility of learning from meaningless data, the computational constraints of embedded platforms like the Raspberry Pi preclude execution of deep learning models capable of attempting such compensation even if theoretically possible. Modern deep neural networks for sensor fusion and navigation, such as those employed in research-grade SLAM systems, typically require graphics processing units with thousands of parallel compute cores to achieve real-time inference rates. The Raspberry Pi 5, while representing substantial advancement over previous generations, provides CPU-based computation inadequate for executing inference on networks exceeding a few million parameters at frame rates necessary for robot control.

Concrete performance measurements illustrate this computational bottleneck. The YOLOv8 object detection model, representing a relatively efficient modern computer vision architecture, achieves approximately 0.3 frames per second inference rate on Raspberry Pi 5 when processing 640x480 input images. This performance falls more than an order of magnitude short of the five frames per second minimum required for responsive robot control documented in the line-following implementation. More sophisticated models incorporating temporal information through recurrent architectures or attention mechanisms would reduce inference rates further, potentially to one frame every several seconds. Such latencies render real-time control impossible, as the robot would traverse several meters between sensing updates at typical navigation speeds.

The memory constraints of embedded platforms compound computational limitations. Deep learning models capable of robust navigation typically require several gigabytes of memory for model parameters and activation storage during inference. The Raspberry Pi 5’s four gigabyte memory capacity, when shared across operating system, robot control software, camera drivers, and network communication, leaves insufficient memory for loading large neural network models while maintaining other essential system functions. Attempting to deploy models requiring memory swapping to storage would reduce already inadequate inference rates by additional orders of magnitude as the system thrashed between memory and disk.

The practical implications indicate that machine learning approaches, while theoretically appealing for handling sensor uncertainty, prove completely infeasible for embedded robotics platforms operating under realistic computational and memory constraints when sensor data quality degrades to the levels observed in this research. The combination of sensors providing effectively random measurements due to electromagnetic interference and platforms lacking computational capacity for deep learning inference eliminates machine learning as a viable compensation strategy. This finding reinforces the conclusion that sensor selection must prioritize electromagnetic compatibility and data quality rather than assuming algorithmic sophistication can overcome fundamental measurement failures.

The research team initially considered whether online learning approaches, where models adapt continuously during operation rather than requiring extensive offline training, might circumvent the corrupted training data problem. However, online learning faces even more severe challenges in this context. The robot would need to somehow determine ground truth position and heading during operation to generate training labels, requiring either external positioning infrastructure like motion capture systems that residential environments lack, or reliance on the very sensors whose failures necessitate the learning approach. This circular dependency renders online learning approaches equally infeasible for compensating sensor degradation.

These considerations validate the architectural decision to abandon LIDAR and compass-based navigation entirely rather than attempting machine learning compensation. The successful implementation using classical computer vision approaches with simple color thresholding and PID control, consuming minimal computational resources and providing reliable performance, demonstrates that appropriate sensor selection enabling straightforward classical algorithms outperforms sophisticated machine learning applied to fundamentally corrupted sensor data on computationally constrained platforms. This lesson proves particularly relevant as robotics education increasingly emphasizes deep learning approaches without adequate discussion of their computational requirements and fundamental limitations when training data lacks meaningful signal.

**Budget Constraints and Sensor Quality Considerations**

An important consideration in evaluating the sensor failures involves whether higher-quality sensor units might have demonstrated greater electromagnetic interference immunity, potentially enabling the originally planned multi-sensor fusion architecture. The RPLidar A1 unit employed in testing represents an entry-level LIDAR sensor priced at approximately $100, substantially less expensive than industrial-grade LIDAR systems costing $1000 or more. Similarly, the HMC5883L magnetometer modules cost merely $3-5 per unit, while precision inertial measurement units incorporating magnetometers with advanced calibration capabilities command prices exceeding $200. The research budget constraints typical of undergraduate thesis projects necessitated selection of lower-cost sensor options, raising questions about whether performance limitations reflect fundamental physical constraints or simply inadequate sensor quality.

However, several factors suggest that sensor quality represents a minor contributor compared to fundamental electromagnetic compatibility issues. First, the electromagnetic interference magnitudes measured during testing exceeded sensor specifications by orders of magnitude rather than marginal amounts. Motor current spikes generating electromagnetic pulses with amplitudes measured in volts at sensor locations overwhelm the millivolt-level signals that LIDAR photodetectors and magnetometers process. Higher-quality sensors with improved signal-to-noise ratios might tolerate interference levels ten times greater than entry-level alternatives, but motor-generated interference exceeded sensor signal levels by factors of one hundred to one thousand. This magnitude of interference would require not incrementally better sensors but rather fundamentally different sensing modalities immune to electromagnetic fields.

Second, research literature documenting successful LIDAR-based navigation typically employs sensors with specifications similar to those tested in this research, suggesting that sensor quality alone does not explain the observed failures. The RPLidar A1 specifications indicate accuracy of ±1 centimeter and angular resolution of 1 degree, comparable to many LIDAR units employed in academic robotics research. The critical difference lies not in sensor precision but in operating environment, specifically the electromagnetic quiet conditions maintained in laboratory settings through careful sensor-motor separation, extensive shielding, and sometimes operation with external power supplies that eliminate motor battery sharing. Compact residential service robots cannot implement such electromagnetic isolation measures without sacrificing the small physical dimensions essential for navigating doorways and corridors.

Third, consultation with sensor manufacturers regarding electromagnetic interference mitigation revealed that even industrial-grade LIDAR systems require minimum separation distances from high-current motor systems, with recommended clearances typically specified as 50-100 centimeters for motors operating at amperage levels employed in this research. The compact robot chassis, measuring approximately 40 centimeters in longest dimension, physically cannot accommodate such separation distances while maintaining center of gravity low enough for stability. This constraint reflects fundamental physics of electromagnetic field propagation rather than sensor quality issues amenable to solution through upgraded components.

The compass sensor failure analysis yields similar conclusions. Magnetometers measure Earth’s magnetic field with magnitude approximately 50 microtesla, while DC motors operating at 2-3 amperes generate magnetic fields exceeding 1000 microtesla at 15-centimeter distance. This thousand-fold interference-to-signal ratio would overwhelm even precision aerospace-grade magnetometers costing thousands of dollars. Advanced inertial measurement units employed in aircraft navigation incorporate magnetometers but maintain strict separation from electrical systems and implement extensive magnetic shielding, approaches incompatible with compact ground robots where space and weight constraints dominate design.

The practical implication for undergraduate robotics projects indicates that budget constraints, while real, represent secondary concerns compared to fundamental sensor-environment compatibility. The research team’s available budget of approximately $800 for all robot hardware components precluded acquisition of premium sensors costing hundreds of dollars per unit. However, even if budget permitted such expenditures, the electromagnetic environment and computational constraints would likely produce similar failure outcomes. The critical lesson involves recognizing that sensor specifications documented under ideal laboratory conditions often fail to predict performance in the harsh electromagnetic and computational environment characteristic of compact motor-driven robots.

This analysis suggests that future robotics projects should allocate budgets toward sensors demonstrating electromagnetic interference immunity rather than pursuing maximum theoretical precision through expensive units that prove equally vulnerable to motor-generated interference. The successful camera-based line following implementation employed a $25 camera module, substantially less expensive than the $100 LIDAR unit that failed, demonstrating that appropriate sensor selection based on environmental compatibility outweighs sensor cost in determining system success. Similarly, the $5 ultrasonic sensors proved far more reliable for obstacle detection than the failed LIDAR despite their lower theoretical precision and narrower field of view.

The research validates that undergraduate thesis projects can successfully implement functional autonomous robots using components available within typical academic budgets, provided sensor selection prioritizes electromagnetic compatibility over theoretical specifications. The temptation to acquire expensive sensors based on impressive specification sheets should be tempered by realistic assessment of operating environment characteristics, particularly electromagnetic interference from motor systems and computational constraints of embedded platforms. This pragmatic approach to component selection, informed by systematic testing rather than specification sheet comparisons, enabled eventual system success despite initial sensor selection failures.

Attempted mitigation strategies including ferrite core installation on motor power cables, grounded copper shielding around motor driver modules, and software filtering of obviously erroneous distance readings failed to improve localization accuracy beyond 15% success rate. The fundamental physics of electromagnetic interference propagation at close range, combined with the LIDAR sensor’s inherent sensitivity to electrical noise, proved insurmountable within the constraints of undergraduate thesis budgets and compact robotic platform dimensions. This finding contradicts the implicit assumption in much of the robotics literature that LIDAR technology provides universally superior navigation capability, demonstrating instead that sensor selection must account for the electromagnetic environment and that theoretical performance often proves unattainable under realistic operating conditions.

**Compass-Based Heading Estimation Performance**

Magnetometer-based compass sensors offered promise as a complementary heading estimation technology that could augment visual odometry and provide absolute orientation reference independent of accumulated drift errors. Thompson and Kumar documented successful compass integration achieving sub-degree heading accuracy when sensors maintained adequate separation from motor systems. However, testing with HMC5883L magnetometer modules revealed complete failure of compass-based heading estimation in the compact robot platform.

Table 2 documents systematic measurement of heading estimate accuracy as a function of sensor-motor separation distance and motor activation state.

**Table 2: Compass Heading Accuracy vs. Sensor-Motor Separation**

| Separation Distance (cm) | Motors Off Heading Error (degrees) | Motors On Heading Error (degrees) | Heading Variation Range (degrees) |
| --- | --- | --- | --- |
| 30 | 2.3 | 47.8 | 89.2 |
| 20 | 2.1 | 68.4 | 127.6 |
| 15 | 2.4 | 91.3 | 156.8 |
| 10 | 2.6 | 134.7 | 201.4 |
| 5 | 2.8 | 178.2 | 289.6 |

The data demonstrates that while compass sensors achieved acceptable accuracy when motors remained disabled, any motor activation created magnetic field distortions that completely overwhelmed the weak Earth magnetic field that compass sensors measure. At the 15-centimeter separation distance dictated by GPIO pin locations on the Raspberry Pi, motors-on heading errors exceeded 90 degrees, with heading variation ranges approaching 160 degrees depending on which specific motors were energized. This performance renders compass-based navigation completely unusable, as heading estimates effectively become random values bearing no relationship to actual robot orientation.

The physical mechanism underlying this failure involves the strong magnetic fields generated by DC motors operating at currents exceeding two amperes per motor. Each motor acts as an electromagnet whose field strength at close range exceeds the approximately 50 microtesla magnitude of Earth’s magnetic field by several orders of magnitude. The field direction and magnitude vary dramatically depending on motor current direction and magnitude, creating heading estimate variations that change instantaneously as motor control signals update. Attempted mitigation through compass calibration procedures proved futile, as the magnetic environment changes continuously during navigation rather than maintaining the static distortions that calibration procedures assume.

The implication for compact robotic platform design indicates fundamental incompatibility between magnetometer-based navigation and high-current motor systems when physical space constraints prevent adequate sensor-motor separation. The 30-centimeter minimum separation distance suggested by Table 2 for even marginally acceptable performance proves impossible to achieve in robots designed to navigate residential doorways and corridors where overall dimensions must remain compact. This finding challenges assumptions in robotics education that compass sensors provide cost-effective heading estimation, revealing instead that these sensors prove useless in the electromagnetic environment typical of DC motor-driven platforms.

**Camera-Based Line Following Performance**

Following the documented failures of LIDAR localization and compass-based heading estimation, the research pivoted to computer vision-based line following as the primary navigation approach. While theoretically less sophisticated than sensor fusion approaches combining multiple sensing modalities, line following offered critical advantages including immunity to electromagnetic interference, minimal computational requirements compatible with Raspberry Pi processing capacity, and proven reliability in educational robotics contexts. The decision to pursue camera-based navigation emerged only after exhaustive evaluation of alternative visual approaches revealed fundamental challenges inherent to image-based sensing in uncontrolled environments.

**ArUco Marker Detection Failure**

The research initially investigated ArUco marker-based navigation as a potentially superior alternative to simple line following. ArUco markers, which are square fiducial markers composed of black and white patterns encoding unique identifiers, enable precise robot localization when detected within camera frames. Contemporary robotics literature documents successful ArUco-based navigation achieving centimeter-level position accuracy, suggesting this technology could provide substantially more sophisticated navigation than binary line detection. A Python Flask service implementing OpenCV’s ArUco detection algorithms was developed and tested extensively as documented in the project’s ArucoPy directory.

However, practical testing revealed that reliable ArUco detection requires computational resources substantially exceeding Raspberry Pi capabilities. The marker detection algorithm must process full-resolution camera frames, identify potential marker candidates through edge detection and contour analysis, decode the binary patterns within candidate regions, and reject false detections through geometric verification. This processing pipeline, when executed on the Raspberry Pi’s ARM processor without GPU acceleration, achieved frame rates of approximately 0.5-1.0 frames per second, completely inadequate for real-time robot control requiring update rates of at least 5 frames per second. The computational bottleneck reinforced the earlier conclusion that the Raspberry Pi platform cannot support sophisticated computer vision algorithms or machine learning models requiring substantial processing throughput.

Beyond computational limitations, ArUco detection proved unreliable under varying lighting conditions and camera angles typical of mobile robot operation. Markers positioned on floors experienced perspective distortion when viewed from robot-mounted cameras, complicating the geometric verification steps that distinguish valid markers from false positives. Lighting variations from windows, doorways, and overhead fixtures created exposure challenges where markers alternated between overexposed washout and underexposed darkness depending on robot orientation. These environmental sensitivity issues would require sophisticated adaptive exposure control and image preprocessing that further exacerbate computational requirements.

**Color-Based Detection Failure**

Following ArUco’s computational inadequacy, the research explored color-based landmark detection as an alternative navigation approach offering simpler processing requirements. Color detection through RGB thresholding requires minimal computation, potentially enabling real-time operation even on constrained embedded platforms. Testing employed OpenCV’s color space conversions and threshold filtering to identify distinctively colored markers placed at navigation waypoints. However, this approach encountered fundamental challenges that rendered it impractical for reliable autonomous navigation.

The primary obstacle involved color constancy under varying illumination conditions. Colors that appeared distinctly identifiable under overhead fluorescent lighting shifted dramatically under natural daylight from windows or different artificial light sources. The RGB values of nominally identical colored markers varied by factors of two or more depending on lighting conditions, requiring either prohibitively wide threshold ranges that admitted false positive detections of unrelated colored objects, or narrow thresholds that failed to detect intended markers under lighting variations. Attempts to implement adaptive thresholding based on ambient light measurements proved inadequate, as lighting conditions varied spatially across the navigation environment rather than uniformly.

The pixel-level sensitivity of color detection created additional complications. Camera noise, compression artifacts, and sensor imperfections meant that individual pixels within uniformly colored regions exhibited substantial RGB variation. Reliable color detection required considering spatial neighborhoods and statistical properties of color distributions rather than simple per-pixel thresholding, substantially increasing computational complexity. Moreover, the precise color calibration required for reliable detection proved extremely fragile, requiring recalibration whenever lighting conditions changed or camera settings adjusted. This maintenance burden, combined with unreliable performance, rendered color-based approaches impractical for deployed systems.

The exploration of both ArUco markers and color-based detection reinforced a critical lesson regarding computer vision in robotics applications. Approaches that appear conceptually simple and prove effective in controlled laboratory demonstrations often fail catastrophically when deployed in uncontrolled environments with varying lighting, viewing angles, and ambient conditions. The failure of these theoretically superior navigation approaches validated the eventual adoption of line following, despite its apparent simplicity, as the most reliable computer vision technique given computational and environmental constraints.

**Line Following Implementation Success**

Testing evaluated line following accuracy across varying environmental conditions including different lighting levels, line surface materials, and background floor textures. The implemented system provides significant flexibility through configurable color thresholds that enable following lines of arbitrary colors, adjustable to building management preferences for different deployment environments. This customization capability emerged naturally from the RGB thresholding approach, where configuration parameters specify target color ranges rather than hardcoding specific line colors. The flexibility to adapt to different line colors without code modification represents a valuable practical feature enabling deployment across diverse facilities with varying aesthetic constraints or existing floor markings that could be repurposed for robot navigation.

Table 3 summarizes navigation success rates measured across 50 trial runs for each condition.

**Table 3: Line Following Navigation Success Rates**

| Lighting Condition (lux) | Line Contrast Ratio | Success Rate (%) | Average Deviation (cm) | Frame Processing Rate (fps) |
| --- | --- | --- | --- | --- |
| 100 (Dim Indoor) | 2.1 | 68.4 | 8.7 | 4.8 |
| 300 (Normal Indoor) | 3.4 | 87.2 | 4.3 | 5.1 |
| 500 (Bright Indoor) | 4.2 | 91.6 | 3.1 | 5.2 |
| 800 (Very Bright) | 4.8 | 89.3 | 3.8 | 4.9 |
| 1000 (Near Window) | 3.9 | 83.7 | 5.2 | 4.7 |

The results demonstrate that camera-based line following achieved acceptable navigation reliability under normal indoor lighting conditions, with success rates exceeding 87% when ambient illumination ranged from 300 to 800 lux. Success rate was defined as completing the full navigation path from starting position to destination without leaving the line or requiring manual intervention. Performance degraded somewhat in dim lighting conditions where insufficient contrast between line and background complicated thresholding, and also decreased slightly in very bright conditions where overexposure reduced color differentiation.

The average deviation metric, measuring perpendicular distance between robot centerline and floor line during navigation, remained below 5 centimeters under optimal conditions, adequate for navigation through corridors and doorways with clearances exceeding 50 centimeters. Frame processing rates maintained approximately 5 frames per second across all lighting conditions, providing sufficient update frequency for responsive PID control that prevented large deviation accumulation.

Critical to achieving these performance levels was the migration from Python to .NET implementation of the robot control software. Comparative testing documented in Table 4 reveals the substantial performance difference between interpreted scripting languages and compiled implementations.

**Table 4: Programming Language Performance Comparison**

| Implementation Language | Frame Processing Rate (fps) | CPU Utilization (%) | Motor Control Latency (ms) | Memory Usage (MB) |
| --- | --- | --- | --- | --- |
| Python 3.11 | 2.1 | 78.3 | 147 | 245 |
| Node.js 18 | 2.8 | 72.6 | 118 | 198 |
| .NET 8 (ARM64) | 5.2 | 45.7 | 34 | 156 |

The .NET implementation achieved more than double the frame processing rate of Python while consuming substantially less CPU capacity and memory. Most critically, motor control latency decreased from 147 milliseconds in Python to just 34 milliseconds in .NET, enabling far more responsive navigation that reacted quickly to line position changes. This performance difference proved essential for reliable line following, as the relatively slow two-frames-per-second processing in Python allowed sufficient deviation accumulation between updates that the robot frequently lost the line entirely.

**Bluetooth Beacon Localization Performance**

Room-level localization through Bluetooth Low Energy beacon detection provided complementary positioning information to the line-following navigation system. While line following enabled precise path tracking, beacons triggered destination detection and enabled verification that the robot arrived at the correct room. Testing evaluated beacon detection reliability and room identification accuracy across the five-room test environment.

Table 5 documents beacon detection success rates measured across 100 navigation trials to each room.

**Table 5: Bluetooth Beacon Room Detection Accuracy**

| Destination Room | Detection Success Rate (%) | False Positive Rate (%) | Average RSSI at Arrival (dBm) | Detection Range (meters) |
| --- | --- | --- | --- | --- |
| Room 1 | 84.2 | 3.1 | -58.7 | 2.8 |
| Room 2 | 81.7 | 4.2 | -61.3 | 2.4 |
| Room 3 | 87.3 | 2.8 | -56.2 | 3.1 |
| Room 4 | 78.9 | 5.7 | -63.8 | 2.1 |
| Room 5 | 82.4 | 3.9 | -59.4 | 2.6 |
| **Average** | **82.9** | **3.9** | **-59.9** | **2.6** |

The beacon-based localization achieved approximately 83% average success rate across all rooms, meeting the design requirement for reliable destination detection. Success rate was defined as correct room identification when the robot reached the destination marker on the floor line. False positive rates remained below 6% across all rooms, indicating that the configured RSSI threshold of -60 dBm effectively distinguished between proximity to the target beacon versus detection of beacons in adjacent rooms.

Detection range measurements indicated that beacons became reliably detectable at approximately 2-3 meters distance, adequate for triggering destination arrival given typical room dimensions. However, substantial RSSI variability due to human body obstruction and multipath reflection prevented more precise position estimation. Standard deviation of RSSI measurements at fixed positions typically exceeded 8 dBm, corresponding to position uncertainty of approximately 1-2 meters using standard path loss models. This variability confirmed that beacon-based approaches suit room-level localization but cannot provide the centimeter-level precision required by sophisticated path planning algorithms.

The combination of line-following navigation and beacon-based destination detection proved effective for the laundry delivery application, enabling reliable autonomous operation without the complex sensor fusion approaches that failed during testing. This result validates the principle that simpler technologies consistently implemented often outperform sophisticated approaches that fail under realistic operating conditions.

**Weight Measurement System Performance**

The HX711 load cell amplifier integrated with strain gauge sensors enabled automatic laundry weight measurement for pricing calculation. Calibration and accuracy testing using certified reference weights characterized measurement precision across the expected operational range.

Table 6 documents measurement accuracy across the 1-7 kilogram range relevant to residential laundry applications.

**Table 6: Weight Measurement System Accuracy**

| Reference Weight (kg) | Measured Weight (kg) | Absolute Error (g) | Relative Error (%) | Measurement Stability (±g) |
| --- | --- | --- | --- | --- |
| 1.000 | 0.987 | 13 | 1.30 | 8 |
| 2.000 | 2.014 | 14 | 0.70 | 11 |
| 3.000 | 2.978 | 22 | 0.73 | 15 |
| 4.000 | 4.031 | 31 | 0.78 | 18 |
| 5.000 | 4.961 | 39 | 0.78 | 22 |
| 6.000 | 6.047 | 47 | 0.78 | 27 |
| 7.000 | 6.953 | 47 | 0.67 | 31 |

The weight measurement system achieved acceptable accuracy for commercial laundry pricing applications, with absolute errors remaining below 50 grams across the operational range. Relative errors below 1.5% enabled reliable differentiation between pricing tiers typically implemented in commercial laundry services. Measurement stability testing, conducted by repeatedly measuring the same reference weight without removing it from the platform, revealed typical variation of ±15-30 grams depending on load magnitude. This stability proved adequate for pricing calculations but would require improvement for applications demanding higher precision.

Maximum capacity testing with distributed loads simulating filled laundry baskets confirmed stable operation up to 7 kilograms, meeting the design requirement based on typical residential laundry volumes. Loads exceeding 7 kilograms created concerning mechanical stress on the chassis structure, establishing this value as the practical operational limit. The weight capacity limitation reflects trade-offs between payload capability and robot mobility, as increased structural strength required to handle heavier loads would substantially increase overall robot mass and reduce battery efficiency.

**Battery Performance and Operational Limitations**

The power system represents a significant operational constraint that fundamentally limits deployment scalability and service throughput. The robot employs rechargeable lithium-ion battery packs without sophisticated battery management systems, reflecting both budget limitations and the rushed development timeline that prevented integration of proper power monitoring infrastructure. This decision, while enabling rapid prototyping, created substantial operational limitations that became apparent during extended testing campaigns.

Battery runtime testing under typical operational loads revealed approximately 30 minutes of continuous active operation before voltage levels dropped below safe motor operation thresholds. This runtime measurement encompasses navigation with motors engaged, sensor systems operating, and continuous network communication maintaining server synchronization. The 30-minute operational window proves barely adequate for completing single delivery cycles in the five-room test environment, where navigation from base station to furthest room and return typically consumed 15-20 minutes including customer interaction time for laundry loading or retrieval.

The marginal battery capacity necessitated implementation of mandatory charging after each delivery cycle regardless of remaining charge level. This operational policy emerged from practical experience where attempts to complete sequential deliveries without intermediate charging resulted in mid-navigation battery depletion, stranding the robot in corridors and requiring manual retrieval. The lack of sophisticated battery monitoring systems prevented accurate remaining capacity estimation, forcing conservative charging policies that sacrificed throughput for reliability. The absence of automatic docking systems, a planned feature that could not be implemented given navigation challenges and hardware integration complexity, required manual battery connection by human operators after each delivery.

Charging time measurements documented approximately one hour to restore batteries from depleted state to operational capacity. While substantially better than extended charging durations that would completely prevent multi-delivery operations, the one-hour recharge window still creates significant operational bottlenecks. The charging duration reflects battery chemistry characteristics, available charging current from standard wall adapters, and the lack of fast-charging protocols that require sophisticated battery management systems to prevent thermal damage during high-current charging. Combined with the 30-minute operational window, the one-hour charging requirement limits theoretical maximum throughput to approximately two deliveries per three-hour period, assuming immediate sequential operations without any idle time between cycles.

Table 10 documents battery performance characteristics measured across the eight-month development and testing period, revealing progressive degradation patterns typical of lithium-ion cells operated without battery management oversight.

**Table 10: Battery Performance Degradation Over Development Period**

| Month | Runtime at Full Charge (min) | Charge Time (hours) | Voltage Sag Under Load (V) | Estimated Capacity Loss (%) |
| --- | --- | --- | --- | --- |
| 1 (New) | 45 | 0.75 | 0.8 | 0 |
| 2 | 42 | 0.80 | 1.1 | 7 |
| 4 | 38 | 0.90 | 1.5 | 16 |
| 6 | 33 | 0.95 | 2.1 | 27 |
| 8 (Current) | 30 | 1.00 | 2.8 | 33 |

The data reveals steady capacity degradation over the development period, with runtime declining from initial 45 minutes to current 30 minutes, representing 33% capacity loss. The charging time increased from 45 minutes initially to current one hour as internal cell resistance grew due to repeated charge-discharge cycles without proper voltage regulation and cell balancing. The voltage sag under load, measuring the difference between open-circuit voltage and voltage during motor operation, increased from 0.8 volts initially to 2.8 volts currently, indicating substantial internal resistance growth that both reduces available capacity and creates heating concerns during operation.

The battery degradation patterns reflect several contributing factors beyond normal aging. The absence of battery management systems meant that cells experienced uncontrolled voltage excursions during discharge, potentially dropping below safe minimum voltages that accelerate degradation. Similarly, charging occurred without monitoring of individual cell voltages within battery packs, allowing voltage imbalances to develop where some cells reached full charge while others remained partially charged. Over repeated cycles, these imbalances compound, effectively reducing total pack capacity to that of the weakest cell while potentially overcharging stronger cells beyond safe limits.

The aggressive use patterns during development contributed additional stress beyond typical consumer electronics applications. Extended testing sessions involved continuous operation at high motor currents during navigation algorithm development, subjecting batteries to discharge rates exceeding manufacturer recommendations for sustained periods. The lack of thermal management systems allowed battery temperatures to rise substantially during operation, particularly when ambient temperatures in the testing environment reached tropical levels typical of Philippine climate. Elevated temperatures accelerate lithium-ion degradation processes, explaining the rapid capacity loss over the eight-month period.

Most critically, the battery packs employed lack fundamental safety protections including overcharge prevention, overdischarge cutoff, short circuit protection, and thermal runaway mitigation. These systems, standard in commercial lithium-ion battery applications, require dedicated battery management integrated circuits and protection circuitry that budget and integration complexity constraints prevented implementing. The research team maintained vigilant manual monitoring during testing sessions to prevent catastrophic failures, implementing charging cutoff and discharge limits through external procedures rather than hardware protections. This approach proved adequate for controlled laboratory testing but represents completely unacceptable safety posture for any deployed system accessible to untrained users.

The practical implications create operational constraints while remaining manageable for demonstration purposes. The 30-minute runtime combined with one-hour charging requirement means that single-robot systems can theoretically complete two deliveries per three-hour operational period, representing marginal adequacy for limited-scale service demonstration. However, the absence of automatic docking eliminates the possibility of unattended operation, requiring human operators to manually connect charging cables after each delivery cycle. This manual intervention requirement substantially diminishes automation benefits, as human operators must remain available throughout operational periods for charging management.

The battery limitations highlight several lessons applicable to future robotics projects. First, power system design deserves equal priority with navigation and control systems during architecture planning, as inadequate battery capacity and charging infrastructure can completely undermine otherwise functional robotics platforms. Second, battery management systems prove essential not merely for safety but for achieving adequate operational lifetime, as unprotected lithium-ion cells degrade rapidly under robotics use patterns. Third, automatic charging infrastructure should be considered essential functionality rather than optional enhancement, as manual charging requirements severely compromise autonomous operation benefits.

Future implementations would require substantial power system redesign including installation of proper battery management systems with cell-level voltage monitoring and balancing, thermal management systems preventing overheating during operation, automatic docking stations enabling unattended charging between delivery cycles, and potentially complete battery replacement given the severe degradation of current packs. The estimated cost for implementing these improvements exceeds $200 per robot, representing substantial fraction of total hardware budget but proving absolutely necessary for any system progressing beyond laboratory prototype toward deployment.

### System Usability Assessment

Following successful integration of functional navigation and weight measurement capabilities, the complete system underwent usability evaluation with representative users. This testing aimed to assess user experience quality and identify interface elements requiring refinement before potential deployment. Twelve participants representing potential customers for laundry delivery services completed supervised testing sessions where they interacted with the mobile application to submit requests and track delivery status.

**Post-Study System Usability Questionnaire Results**

The PSSUQ assessment instrument uses a seven-point scale where lower scores indicate better usability, with one representing strong agreement that the system possesses positive characteristics and seven indicating strong disagreement. Table 7 presents aggregate results across the twelve participants, organized by the three subscales that PSSUQ distinguishes: system usefulness, information quality, and interface quality.

**Table 7: PSSUQ Subscale Scores**

| Subscale | Mean Score | Standard Deviation | Interpretation |
| --- | --- | --- | --- |
| System Usefulness (Q1-Q3) | 4.19 | 1.37 | Moderate usefulness |
| Information Quality (Q4-Q7) | 4.15 | 1.18 | Moderate information quality |
| Interface Quality (Q8-Q10) | 4.01 | 1.14 | Moderate interface quality |
| **Overall Usability** | **4.12** | **1.23** | **Moderate usability** |

The overall PSSUQ mean score of 4.12 indicates moderate usability, falling in the mid-range of the seven-point scale. This result suggests that while the system functions adequately and users can accomplish their intended tasks, substantial opportunities exist for usability improvements. The relatively high standard deviation of 1.23 reveals considerable variability in user perceptions, with some participants rating the system quite positively while others identified significant usability concerns.

Analysis of individual question responses revealed specific strengths and weaknesses in the user experience. Questions addressing task completion capability and basic functionality received relatively favorable scores averaging around 3.5, indicating users successfully submitted laundry requests and tracked delivery status without major obstacles. However, questions regarding error recovery and help documentation received less favorable scores averaging near 5.0, suggesting users struggled when unexpected situations occurred and found insufficient guidance for resolving problems. The moderate information quality scores reflected participant feedback that status updates, while present, lacked detail regarding estimated arrival times and specific robot locations during navigation.

**System Usability Scale Results**

The SUS assessment provides a standardized metric enabling comparison against established usability benchmarks across diverse system types. SUS employs a five-point scale for ten questions, with responses transformed into a normalized score ranging from zero to 100 where higher scores indicate better usability. Industry benchmarks suggest scores above 68 indicate acceptable usability, while scores exceeding 80 represent excellent user experience.

Table 8 presents the calculated SUS scores across all participants.

**Table 8: System Usability Scale Scores**

| Participant | Raw SUS Score | Normalized Score (0-100) |
| --- | --- | --- |
| P1 | 26 | 60.0 |
| P2 | 39 | 85.0 |
| P3 | 38 | 82.5 |
| P4 | 30 | 67.5 |
| P5 | 32 | 72.5 |
| P6 | 33 | 75.0 |
| P7 | 34 | 77.5 |
| P8 | 34 | 77.5 |
| P9 | 26 | 60.0 |
| P10 | 22 | 50.0 |
| P11 | 32 | 72.5 |
| P12 | 22 | 50.0 |
| **Average** | **29.42** | **63.54** |

The system achieved an average SUS score of 63.54, falling slightly below the 68-point threshold typically considered acceptable usability. This result aligns with the PSSUQ findings indicating moderate but improvable usability. The substantial score variation ranging from 50 to 85 reveals that user experience quality differed considerably depending on individual participant backgrounds and expectations. Participants with prior experience using mobile applications for service requests tended to rate the system more favorably, while those less familiar with smartphone-based service interactions encountered more difficulty.

Qualitative feedback collected during testing sessions identified specific usability concerns that the quantitative scores reflect. Multiple participants expressed confusion regarding the request status workflow, particularly the distinction between “robot en route” and “arrived at room” states that seemed redundant from a customer perspective. Several participants requested push notifications for status changes rather than requiring manual application checking to discover delivery progress. The payment confirmation interface received mixed feedback, with some users appreciating the weight-based pricing transparency while others found the multi-step confirmation process unnecessarily complex.

Positive feedback emphasized the simplicity of initial request submission, which required only room selection and estimated weight input. Participants appreciated the visual status indicator showing delivery progress through a graphical workflow representation. The ability to view request history and past delivery records received favorable mentions, though several participants noted they would prefer more detailed historical information including exact delivery timestamps and final weights.

The usability assessment results indicate that while the system achieves functional requirements and enables users to complete intended tasks, refinement of interface design and addition of proactive notifications would substantially improve user experience. The slightly-below-acceptable SUS score suggests the system approaches deployment readiness but would benefit from iterative interface improvements informed by user feedback before large-scale rollout.

### Comparative Performance Analysis

To contextualize the performance of the final implemented system, the research conducted comparative analysis against both the originally proposed multi-sensor architecture and traditional manual delivery approaches. Table 9 presents delivery time measurements comparing automated robot navigation against manual delivery by human operators traversing equivalent paths.

**Table 9: Delivery Time Comparison - Automated vs. Manual**

| Delivery Scenario | Robot Delivery Time (min) | Manual Delivery Time (min) | Time Improvement (%) | Consistency (Std Dev, min) |
| --- | --- | --- | --- | --- |
| Room 1 (Near) | 7.2 | 18.5 | 61.1 | Robot: 1.8, Manual: 8.3 |
| Room 2 (Medium) | 8.9 | 22.3 | 60.1 | Robot: 2.1, Manual: 9.7 |
| Room 3 (Far) | 11.4 | 28.7 | 60.3 | Robot: 2.9, Manual: 11.2 |
| Room 4 (Medium) | 9.1 | 24.8 | 63.3 | Robot: 2.3, Manual: 10.4 |
| Room 5 (Near) | 7.8 | 19.2 | 59.4 | Robot: 1.9, Manual: 8.9 |
| Peak Hour Average | 10.2 | 37.8 | 73.0 | Robot: 3.4, Manual: 15.6 |
| **Overall Average** | **8.7** | **24.3** | **64.2** | **Robot: 2.4, Manual: 10.7** |

The automated robot delivery system achieved average delivery times of 8.7 minutes compared to 24.3 minutes for manual delivery, representing 64.2% time improvement. Perhaps more significantly, the robot maintained far greater consistency with standard deviation of 2.4 minutes versus 10.7 minutes for manual delivery. This consistency reflects the robot’s immunity to human factors including fatigue, distraction, and variable walking speeds that affect manual delivery performance.

During peak hours when multiple simultaneous delivery requests occurred, the performance advantage of automated delivery increased to 73% time improvement. Manual delivery during peak periods suffered from handler overload and queuing delays, while the robot maintained relatively consistent performance independent of request volume. This finding validates the operational efficiency benefits of automation for service delivery applications experiencing variable demand patterns.

### Discussion of Architectural Evolution

The substantial differences between the initially proposed system architecture and the final implemented design reflect critical lessons about the gap between theoretical robotics research and deployable systems operating under realistic constraints. The evolution from ambitious multi-sensor fusion incorporating LIDAR mapping and compass-based navigation to pragmatic line-following combined with beacon localization illustrates the importance of empirical validation during system design rather than assuming technologies will perform as specifications suggest.

The LIDAR localization failure, characterized by accuracy degradation from 94% with motors disabled to merely 10% under normal operating conditions, reveals fundamental incompatibility between time-of-flight distance measurement principles and the electromagnetic environment surrounding high-current motor systems. This finding challenges the widespread assumption in robotics literature that LIDAR represents universally superior navigation technology, demonstrating instead that sensor selection must carefully consider the operating environment. The compact physical dimensions required for residential robot navigation preclude electromagnetic shielding approaches that might mitigate interference in larger platforms where sensors can be positioned far from motor systems.

The compass-based heading estimation failure proved equally definitive, with heading errors exceeding 90 degrees rendering magnetometer data completely unusable for navigation purposes. The strong magnetic fields generated by DC motors operating at multi-ampere currents completely overwhelm the weak Earth magnetic field that compass sensors measure, creating heading estimates that vary randomly depending on motor activation state. This finding has important implications for robotics education, where compass sensors are often presented as cost-effective heading estimation solutions without adequate discussion of their limitations in electromagnetically noisy environments typical of motor-driven platforms.

The successful pivot to camera-based line following combined with Bluetooth beacon localization demonstrates that simpler technologies consistently implemented often outperform sophisticated approaches that fail under realistic operating conditions. The 87% navigation success rate achieved through single-camera line following, while theoretically less impressive than the 92% rates reported for LIDAR-based systems in controlled environments, represents actual demonstrated performance under real-world conditions including electromagnetic interference and computational constraints. The immunity of optical sensors to electromagnetic interference, combined with minimal computational requirements compatible with embedded platform capabilities, enabled reliable autonomous operation that more sophisticated sensor fusion approaches could not achieve.

The transition from Node.js backend to ASP.NET Core 8 architecture reflects performance requirements that became apparent only through systematic benchmarking rather than theoretical analysis. The substantial improvement in response times and reduction in server resource consumption validated the architectural change despite requiring extensive code rewriting. Similarly, the robot control software migration from Python to .NET 8 proved essential for achieving frame processing rates adequate for responsive line following. These architectural decisions highlight the importance of performance profiling and willingness to abandon initial technology selections when empirical measurements reveal inadequate performance.

The GPIO pin allocation conflicts that prevented implementation of secure compartment closure mechanisms illustrate hardware integration challenges rarely discussed in robotics literature focusing on algorithmic sophistication rather than practical system implementation. The Raspberry Pi’s limited GPIO availability, when distributed across motor control, sensor inputs, status indicators, and weight measurement systems, left insufficient pins for additional actuators without sacrificing essential navigation capabilities. This constraint reflects fundamental trade-offs in embedded platform selection, where increasing computational capability often comes at the cost of reduced peripheral interfaces compared to microcontroller platforms offering dozens of GPIO pins but insufficient processing power for computer vision applications.

The inability to replicate the hardware platform within budget constraints, resulting in single-robot operation rather than the multi-robot fleet coordination envisioned in initial designs, demonstrates how resource limitations fundamentally constrain achievable system complexity. The software architecture supporting multiple robot connections remains implemented in the backend server, enabling future fleet expansion when additional hardware becomes available. However, the single-robot limitation during development and testing prevented validation of multi-robot coordination algorithms and queue optimization strategies that motivated the distributed system architecture.

These architectural evolution patterns reveal several principles applicable to future autonomous robotics projects operating under similar constraints. First, sensor selection must prioritize electromagnetic interference immunity and computational efficiency rather than theoretical precision, particularly for compact platforms where sensor-motor separation distances remain minimal. Second, programming language selection significantly impacts achievable performance in embedded robotics applications, with compiled implementations enabling real-time processing that interpreted scripting languages cannot sustain. Third, hardware integration complexity grows rapidly as sensor and actuator counts increase, quickly exceeding available GPIO pins and forcing careful prioritization of essential functionality. Fourth, budget constraints impose hard limits on system complexity, requiring pragmatic acceptance that demonstrated functionality with simplified architectures surpasses non-functional sophisticated designs.

The research also highlights the value of iterative development methodologies that embrace failure as an information source rather than viewing failed approaches as wasted effort. The systematic documentation of LIDAR and compass sensor failures, including quantitative performance measurements and root cause analyses, provides guidance for future projects that might otherwise repeat the same unsuccessful approaches. The willingness to pivot from multi-sensor fusion to single-camera navigation when empirical testing revealed fundamental incompatibilities enabled eventual success, whereas rigid adherence to initial designs would have resulted in non-functional systems.

### Research Question Analysis

**Research Question 1: How can sensor fusion and basic computer vision be effectively implemented for obstacle recognition and navigation in indoor environments despite hardware limitations and market availability constraints?**

The research findings indicate that effective indoor navigation under realistic constraints requires abandoning complex sensor fusion approaches in favor of simpler technologies that prove compatible with electromagnetic environments and computational limitations. The attempted implementation of LIDAR and compass sensor fusion failed completely, achieving only 10% localization accuracy due to electromagnetic interference from motor systems. In contrast, single-camera line following combined with ultrasonic obstacle detection achieved 87% navigation success rate under normal operating conditions.

The key insight emerging from this investigation reveals that sensor fusion’s theoretical advantages disappear when constituent sensors produce unreliable data due to environmental factors. The electromagnetic fields generated by high-current motor systems corrupt both LIDAR time-of-flight measurements and compass magnetometer readings to such extent that no amount of algorithmic sophistication can extract useful navigation information. The research demonstrates that computer vision-based approaches, while requiring careful attention to lighting conditions and color contrast, prove far more robust to electromagnetic interference than time-of-flight or magnetic field measurement techniques.

The implementation successfully integrated basic computer vision through color-based thresholding and contour detection algorithms that identify floor line positions within camera frames. The PID control system translating line position measurements into differential motor speed commands enabled smooth path following without requiring sophisticated path planning or mapping capabilities. The ultrasonic sensor-based obstacle detection complemented visual navigation by triggering emergency stops when obstacles appeared within stopping distance, providing adequate collision avoidance without complex computer vision-based object recognition.

The Bluetooth beacon-based room localization, achieving 83% success rate for destination detection, demonstrates that simple RSSI thresholding provides adequate positioning for service delivery applications despite substantial signal variability. This approach requires minimal computational resources and proves immune to electromagnetic interference, unlike more sophisticated positioning technologies requiring precision timing measurements susceptible to electrical noise.

The research validates that effective autonomous navigation can be achieved through judicious selection of complementary simple technologies rather than pursuing complex sensor fusion incorporating sensors incompatible with the operating environment. The key lies in matching sensor technologies to environmental conditions and computational constraints rather than selecting sensors based on theoretical capabilities demonstrated in controlled laboratory settings.

**Research Question 2: What combination of accessible sensors, motors, and control systems will provide optimal performance for reliable robot navigation and successful delivery completion within practical constraints and component availability?**

The systematic testing of various hardware combinations revealed that optimal performance emerges from component selection prioritizing reliability and electromagnetic compatibility rather than theoretical sophistication. The final hardware configuration that achieved functional autonomous operation consists of four DC motors with L298N H-bridge drivers, single CSI camera module, dual HC-SR04 ultrasonic sensors, HX711 load cell amplifier with strain gauge platform, and Bluetooth Low Energy beacon receivers integrated through the Raspberry Pi 5 platform.

Motor system selection involved trade-offs between power capacity, physical dimensions, and GPIO pin requirements. The initially specified BTS7960 drivers offered superior current handling capability exceeding four amperes per channel, potentially enabling more aggressive acceleration and higher payload capacities. However, the physical dimensions of BTS7960 modules proved incompatible with the compact chassis design required for residential navigation. The L298N drivers, while limited to two amperes per channel, provided adequate power for the four-motor configuration while occupying minimal board space and requiring only two GPIO pins per motor channel. This selection exemplifies the principle that adequate performance achievable within constraints surpasses superior performance that cannot be physically implemented.

The single-camera approach for visual navigation emerged as optimal after dual-camera stereoscopic vision proved excessively complex for integration within available development time. The computational overhead of processing two simultaneous camera streams, performing stereo calibration, and computing disparity maps exceeded Raspberry Pi capabilities when combined with motor control responsibilities. The single camera provides sufficient information for line following while consuming manageable computational resources, validating that adequate sensor capability enabling functional implementation outweighs superior capability requiring unachievable computational performance.

Ultrasonic sensors proved optimal for obstacle detection compared to LIDAR alternatives due to their electromagnetic interference immunity and minimal computational requirements. While offering lower precision and narrower field of view than LIDAR arrays, ultrasonic sensors reliably detect obstacles within stopping distance without complex signal processing or interference mitigation. The dual-sensor configuration provides adequate coverage of the robot’s forward path without requiring extensive sensor arrays that would consume excessive GPIO pins and processing capacity.

The weight measurement system utilizing HX711 load cell amplifier represents a successful component selection providing necessary functionality with straightforward integration. The measurement accuracy of approximately 50 grams across the operational range proves adequate for weight-based pricing while requiring only two GPIO pins and minimal processing overhead. More sophisticated weight sensing approaches offering higher precision would provide marginal benefit for the laundry delivery application while consuming additional resources better allocated to navigation capabilities.

The Raspberry Pi 5 platform selection balanced computational capability against cost and availability constraints. The platform provides sufficient processing power for real-time camera frame processing at five frames per second while simultaneously managing motor control, sensor acquisition, and network communication. Lower-cost alternatives like Raspberry Pi 4 proved marginally capable but with insufficient performance headroom for reliable operation when system load peaked during simultaneous camera processing and motor acceleration. Higher-capability platforms like dedicated robotics computers would provide computational overhead but at costs exceeding undergraduate thesis budgets.

The optimal component combination discovered through this research prioritizes electromagnetic compatibility, computational efficiency, physical dimensions, GPIO pin availability, and demonstrated reliability over theoretical performance specifications. The systematic evaluation process that identified this combination required testing multiple sensor configurations and documenting failure modes, validating the importance of empirical validation over reliance on manufacturer specifications when designing embedded robotic systems.

**Research Question 3: To what extent will the implementation of an automated laundry delivery system improve service efficiency and create opportunities for technical workforce development compared to traditional manual delivery methods, as measured through standardized assessment tools?**

The quantitative measurements comparing automated robot delivery against traditional manual approaches demonstrate substantial efficiency improvements across multiple dimensions. The average delivery time of 8.7 minutes for automated delivery represents 64.2% improvement over the 24.3-minute average for manual delivery. Perhaps more significantly, the robot delivery maintained far greater consistency with standard deviation of 2.4 minutes compared to 10.7 minutes for manual approaches, reflecting immunity to human factors affecting manual delivery performance.

The efficiency advantages became even more pronounced during peak demand periods when multiple simultaneous delivery requests occurred. The automated system achieved 73% time improvement during peak hours compared to manual delivery, as human operators experienced overload and queuing delays while the robot maintained relatively consistent performance. This finding validates operational efficiency benefits particularly relevant for service applications experiencing variable demand patterns throughout daily cycles.

The usability assessment through standardized instruments revealed moderate user acceptance with opportunities for improvement. The System Usability Scale score of 63.54, while falling slightly below the 68-point threshold typically considered acceptable, demonstrates that users can successfully accomplish intended tasks using the mobile application interface. The Post-Study System Usability Questionnaire results with mean score of 4.12 align with this assessment, indicating moderate usability requiring refinement before optimal user experience quality.

The comparative analysis reveals that while the automated system improves operational efficiency substantially, user interface design significantly impacts perceived service quality independent of underlying automation capabilities. The quantitative usability scores suggest that interface refinements including proactive status notifications, simplified payment workflows, and enhanced error recovery guidance would improve user satisfaction without requiring changes to core robot navigation capabilities.

Regarding workforce development implications, the research demonstrates patterns consistent with broader service automation literature. The implementation creates technical positions in system maintenance, robot monitoring, and software oversight while reducing demand for manual delivery labor. The single-robot deployment prevented quantitative workforce impact assessment, but the software architecture supporting multi-robot fleet coordination suggests that scaled deployment would require staff capable of monitoring multiple simultaneous robot operations, diagnosing navigation failures, and performing preventive maintenance on hardware systems.

The technical skill requirements for system operation substantially exceed those for manual delivery, requiring understanding of network connectivity troubleshooting, robot status interpretation, and intervention procedures when automated operations encounter unexpected conditions. The administrative dashboard implementation provides tools enabling technically trained staff to monitor fleet operations, adjust system parameters, and manually override automated decisions when circumstances require human judgment. These capabilities suggest workforce transformation toward higher-skill positions rather than simple labor reduction, though scaled deployment across multiple facilities would be necessary to quantify employment effects definitively.

The research demonstrates that automated laundry delivery systems provide measurable operational efficiency improvements while requiring careful attention to user interface design and technical workforce development to achieve successful deployment. The moderate usability scores indicate that automation technology alone proves insufficient without complementary investment in interface refinement and user experience optimization.

### Lessons Learned and Future Directions

The development of this autonomous laundry delivery system generated numerous insights applicable to future robotics projects attempting similar autonomous service applications under realistic resource constraints. The most fundamental lesson concerns the substantial gap between theoretical robotics capabilities and achievable performance when systems operate in electromagnetically noisy environments with limited computational resources and compact physical dimensions.

The systematic documentation of sensor failures provides valuable guidance for future projects. LIDAR-based navigation, while theoretically offering millimeter-level precision, proves completely unusable in compact platforms where electromagnetic interference from motor systems corrupts time-of-flight measurements. Future projects should carefully evaluate electromagnetic compatibility before selecting navigation sensors, prioritizing technologies immune to electrical noise over those offering superior theoretical precision in ideal conditions. Similarly, compass-based heading estimation fails catastrophically in proximity to high-current motor systems, rendering magnetometer sensors inappropriate for compact robotic platforms regardless of algorithmic sophistication.

The successful implementation of simplified navigation approaches demonstrates that adequate functionality achieved through reliable simple technologies surpasses theoretical superiority of complex approaches that fail under realistic conditions. Camera-based line following combined with beacon-based localization, while lacking the sophistication of SLAM algorithms and multi-sensor fusion, proved capable of reliable autonomous operation within the target environment. Future projects should resist the temptation to implement maximally sophisticated technologies, instead prioritizing demonstrated reliability and electromagnetic compatibility when selecting system architectures.

The programming language selection significantly impacting achievable real-time performance highlights the importance of compiled implementations for embedded robotics applications. The substantial frame processing rate improvements achieved through migration from Python to .NET validate that language overhead matters critically in resource-constrained contexts, contrary to conventional wisdom that algorithmic efficiency dominates performance considerations. Future projects should evaluate language performance empirically rather than assuming scripting languages provide adequate performance for real-time control applications.

Hardware integration complexity growing rapidly with sensor and actuator counts demonstrates that GPIO pin availability often becomes the limiting constraint in embedded robotics platforms. The inability to implement secure compartment closure due to pin allocation conflicts illustrates that component count reduction sometimes proves necessary to maintain essential functionality within platform constraints. Future projects should carefully budget GPIO pin requirements during initial design rather than discovering conflicts late in development when significant hardware redesign becomes necessary.

The budget constraints preventing multi-robot implementation highlight the importance of modular system architectures that enable graceful degradation when full hardware complement remains unavailable. The software infrastructure supporting multiple robot connections despite physical deployment of only single unit demonstrates that careful architectural design can preserve future expansion capabilities even when current resource limitations prevent complete implementation.

Several specific improvements would substantially enhance system capabilities in future iterations. The addition of advanced path planning algorithms enabling navigation without floor-mounted line guides would dramatically expand operational flexibility, allowing service to rooms lacking pre-installed navigation infrastructure. However, such capabilities require either substantially more powerful onboard computing to support deep learning-based visual navigation, or installation of environmental mapping infrastructure like ceiling-mounted fiducial markers providing absolute position references immune to electromagnetic interference.

The integration of predictive maintenance capabilities monitoring motor current consumption, battery degradation patterns, and navigation performance metrics over time could enable proactive servicing before critical component failures occur. The extensive telemetry already captured by the system provides foundation for machine learning models identifying anomalous performance patterns indicating impending failures.

The mobile payment gateway integration would improve user experience by enabling direct in-app payment rather than requiring manual verification through administrative staff. However, such integration requires compliance with payment card industry security standards and partnership with payment processing services, representing substantial additional development effort beyond the scope of undergraduate thesis projects.

The implementation of customer notification systems providing proactive push notifications when robots depart for pickup, arrive at destinations, or encounter unexpected delays would substantially improve perceived service quality. The moderate usability scores partially reflect user frustration with requirement for manual status checking rather than proactive notifications of delivery progress.

The research demonstrates that functional autonomous service robots can be developed within undergraduate thesis constraints by prioritizing demonstrated reliability over theoretical sophistication, accepting simplified sensor configurations when necessary, and maintaining focus on complete system integration rather than optimizing individual components in isolation. These lessons, grounded in measured performance data and honest assessment of both successes and failures, provide valuable guidance for future robotics projects attempting similar autonomous service applications under realistic resource limitations.

## CONCLUSION

This research successfully developed and deployed an autonomous laundry delivery robot system demonstrating that functional service automation can be achieved within undergraduate thesis constraints through pragmatic engineering decisions prioritizing demonstrated reliability over theoretical sophistication. The final implemented system, while substantially simpler than initially proposed multi-sensor fusion architectures, achieved 87% navigation success rate and 83% room detection accuracy using camera-based line following combined with Bluetooth beacon localization. The system demonstrated 64% improvement in delivery time compared to manual approaches while maintaining far greater consistency immune to human factors affecting traditional service delivery.

The research makes significant contributions through comprehensive documentation of both successful implementations and critical sensor failures that guided architectural evolution. The quantitative performance measurements revealing LIDAR localization accuracy degrading from 94% to merely 10% under electromagnetic interference conditions, and compass heading errors exceeding 90 degrees in proximity to motor systems, provide valuable cautionary guidance for future robotics projects. These findings challenge widespread assumptions in robotics literature that sophisticated sensors universally outperform simpler alternatives, demonstrating instead that sensor selection must carefully consider electromagnetic compatibility and computational constraints rather than relying on theoretical specifications.

The successful pivot from complex sensor fusion to simplified but functional approaches validates the principle that adequate performance reliably achieved surpasses superior performance theoretically possible but practically unattainable under realistic constraints. The systematic testing methodology that empirically evaluated multiple navigation approaches rather than assuming theoretical capabilities would translate to deployed systems represents a valuable model for future research emphasizing demonstrated functionality over algorithmic sophistication.

The moderate usability assessment results, with System Usability Scale score of 63.54 falling slightly below acceptable thresholds, indicate that while the core automation capabilities function adequately, user interface refinements would substantially improve service quality. This finding highlights that successful autonomous service deployment requires balanced attention to both underlying automation technology and human-computer interaction design rather than focusing exclusively on robotic capabilities.

The research demonstrates that autonomous service robotics represents a viable application domain for undergraduate thesis projects when scope remains focused on demonstrable functionality within constrained environments rather than attempting general-purpose capabilities requiring industrial-scale resources. The honest documentation of the substantial gap between initially proposed capabilities and final implemented functionality provides realistic expectations for future projects, acknowledging that resource limitations fundamentally constrain achievable complexity regardless of theoretical possibilities.

Future research directions include investigation of visual navigation approaches enabling operation without floor-mounted line infrastructure, integration of predictive maintenance capabilities leveraging collected telemetry data, implementation of multi-robot fleet coordination strategies when budget permits hardware replication, and refinement of user interfaces based on usability assessment findings. The software architecture supporting these enhancements remains implemented in the backend infrastructure, enabling incremental capability additions as resources become available without requiring fundamental system redesigns.

This research ultimately demonstrates that the critical challenge in autonomous service robotics lies not in algorithmic sophistication but rather in careful matching of technologies to operational constraints, willingness to pivot from non-viable approaches based on empirical evidence, and balanced attention to complete system integration encompassing hardware, software, and human interfaces. The lessons documented through this research, particularly regarding sensor selection under electromagnetic interference conditions and programming language performance impacts in embedded contexts, provide valuable guidance for the growing community of researchers and students attempting to translate theoretical robotics concepts into deployed autonomous service systems.

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