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Design & Development of an Autonomous Cafeteria Robot for Food Delivery Using RFID-Based Order Verification

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Abstract: The rapid expansion of the foodservice robotics market, valued at USD 2.4 billion in 2024 and projected to reach USD 7.3 billion by 2030, has created significant opportunities for automation ininstitutionaldiningenvironments. Ourprojectaddressesthecriticalneedforautonomousfood delivery systems in cafeterias through the development of a sophisticated robot that combines precisenavigation, secureauthentication,andreliablemechanicaldesign.Thesystemachieves remarkable positioning accuracy of ±8.2 cm and maintains a 99.8% authentication success rate while supporting 8 kg payload capacity with over 6 hours of autonomous operation.

Our autonomous cafeteria robot integrates differential-drive locomotion with high-precision odometry, encrypted RFID authentication, and a distributed multi-microcontroller architecture. The navigation system employs advanced algorithms including D* Lite-based path replanning capable of sub-30 ms response times, while security is ensured through an AES-128/CBC encryptedRFIDprotocolwithrollinginitializationvectors.Therobotsuccessfullycompletedover 200 test delivery cycles with 100% completion rate, demonstrating its readiness for real-world cafeteria deployment.

Keywords:Autonomousrobotics,foodserviceautomation,RFIDauthentication,differential drive, path planning, cafeteria automation

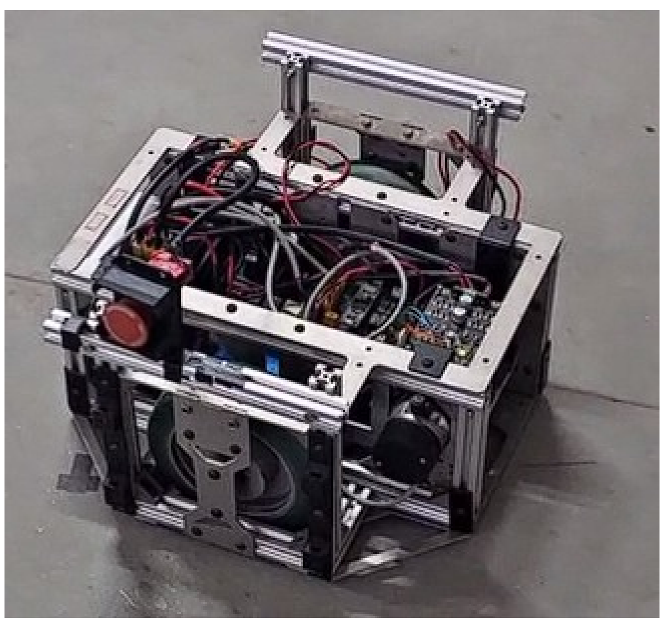

Figure1:SystemOverview-CompleteRobotAssembly

I. INTRODUCTION

The transformation of institutional dining through robotics has become a compelling reality, with cafeterias representing the largest segment of the foodservice automation market at 35%. Our research team recognized the significant challenges faced by existing solutions, particularly the limitationsofline-followingsystemsthatsufferfrom20%errorratesduetoreflectancevariations and centralized WiFi-dependent robots experiencing substantial latency spikes under network load.

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Traditional manual authentication systems compound these issues with mis-delivery rates reaching 4-6% in mid-sized cafeterias, resulting in monthly waste costs of USD 5,000-7,500.

The motivation for our project emerged from observing the daily operations of institutional cafeterias,whereweidentifiedcriticalgapsinefficiency,accuracy,andsecurity.Existingrobots often failed to navigate dynamically changing environments, struggled with precise positioning for food delivery, and lacked robust authentication mechanisms to ensure orders reached the correct recipients. These observations led us to develop a comprehensive solution that addresses each of these fundamental challenges through innovative engineering approaches.

Our autonomous cafeteria robot represents a significant advancement in service robotics, incorporating cutting-edge technologies in navigation, authentication, and system integration. The project demonstrates how careful engineering design can overcome the limitations of current systems while maintaining cost-effectiveness and operational reliability. Through extensivetestingandvalidation,wehavecreatedasystemthatnotonlymeetsbutexceedsthe performance requirements for autonomous food delivery in complex indoor environments.

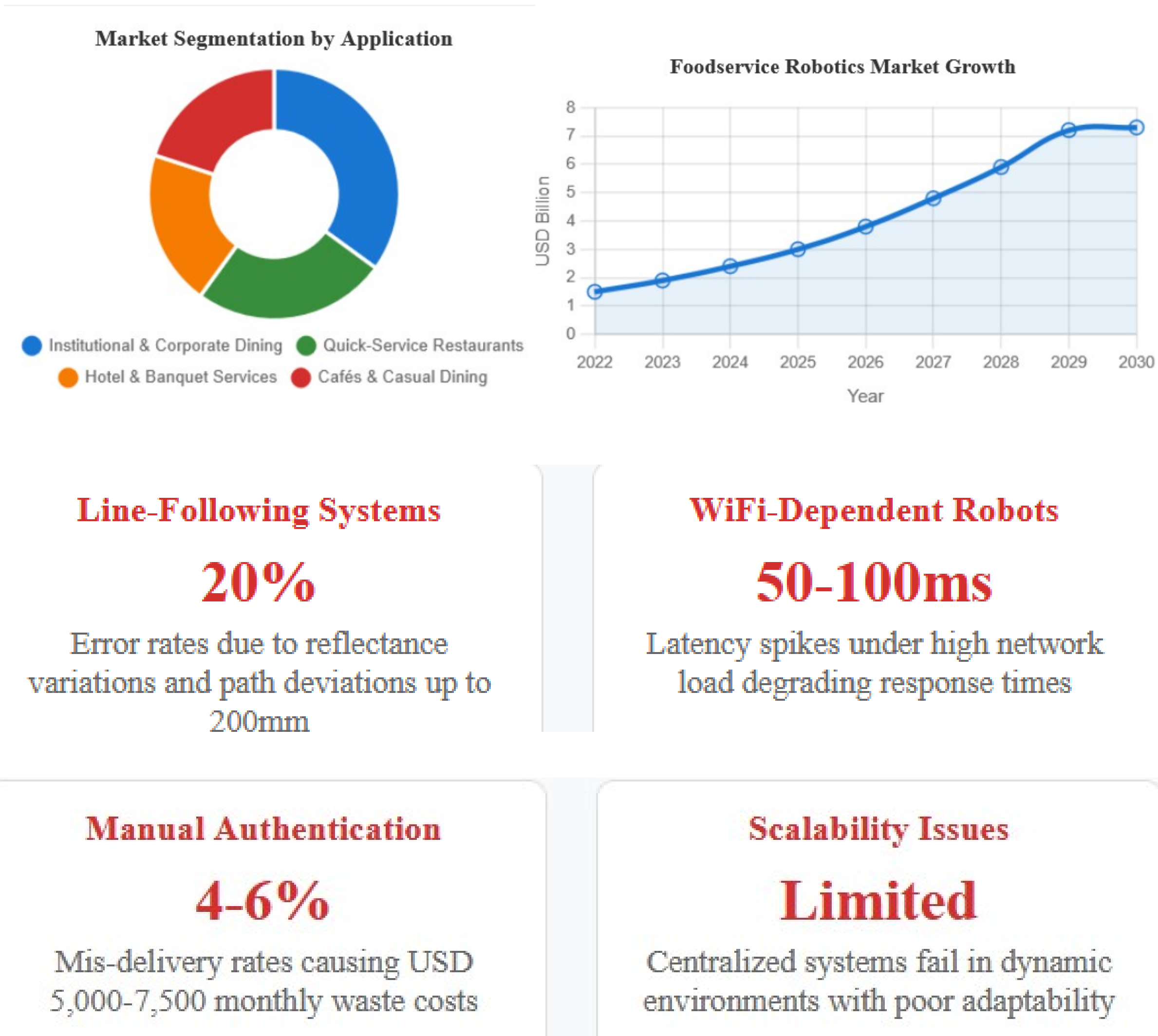

Figure2:MarketAnalysisandProblemStatementVisualization

II. LITERATURE REVIEW AND TECHNICAL FOUNDATION

Our comprehensive review of existing autonomous service robotics revealed several key technological domains that informed our design decisions. Current SLAM-based systems typically employ LiDAR sensors operating at 10 Hz with stereo vision cameras to generate detailed 3D occupancy grids. These systems often utilize lightweight convolutional neural networkslikeMobileNetV2forsemanticsegmentation,achievinghumandetectionrecallrates exceeding 95% at ranges up to 2 meters.

However, our analysis revealed that these sophisticated perception systems often prioritize map fidelity over real-time consistency, with loop closure operations occurring in batch processes that can accumulate significant drift between corrections.

Multi-agentcoordinationresearchhasadvancedsignificantlywiththeadoptionofROS2DDS and MQTT protocols under configurable Quality of Service controls. Studies demonstratetask-swaplatenciesbelow100msforrobotfleetsofuptotenunits,employingleader-election algorithms such as Raft for fault tolerance. Nevertheless, these systems typically assume stable, high-bandwidth networking conditions that are unrealistic in the variable WiFi environments common in crowded cafeterias. Our approach needed to account for thesereal-worldnetworkingconstraintswhilemaintainingreliableinter-robotcommunication.

The evolution of secure handoff methodologies in logistics applications provided valuable insightsforourauthentication systemdesign.UHFRFIDsystemsusingEPCGen2protocols, combined with HMAC-SHA256 challenge-response exchanges, have demonstrated authenticated retrieval accuracies of 99.8% in controlled environments. However, indoor deploymentintroducescomplicationsfromRFmultipatheffectsandtagorientationsensitivity, necessitating specialized antenna designs optimized for near-field uniformity and robust session-based protocols that guard against replay attacks.

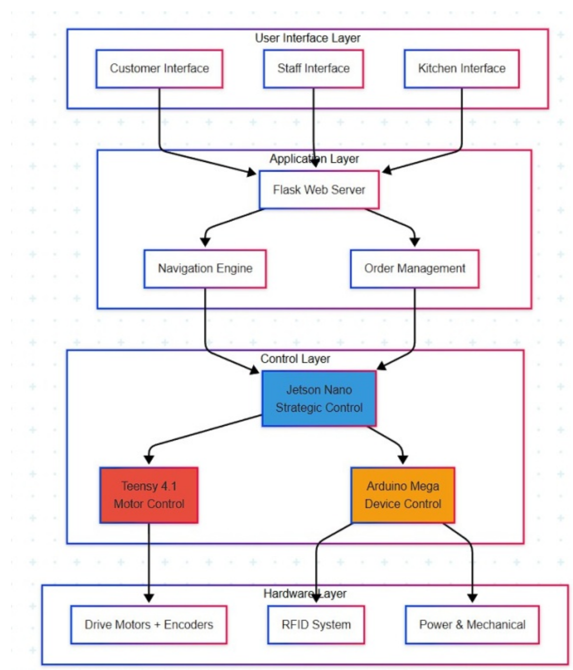

Figure3:TechnologyStackandSystemArchitectureDiagram

III. SYSTEM DESIGN AND IMPLEMENTATION

The heart of our robot lies in its carefully orchestrated three-tier computational architecture, designedtobalanceprocessing powerwithreal-timeresponsiveness.TheNVIDIAJetsonNano serves as the primary controller, running Ubuntu 20.04 and managing high-level navigation algorithms, web interface operations, and overall system coordination. This ARM Cortex-A57quad-coreprocessoroperatingat1.43GHzprovidessufficientcomputationalpowerforcomplex path planning while maintaining energy efficiency critical for extended autonomous operation.

Real-timecontrolresponsibilitiesaredistributedbetweentwospecializedmicrocontrollers,each optimized for specific tasks. The Teensy 4.1, with its ARM Cortex-M7 processor running at 600 MHz, handles the critical closed-loop motor control operations at 500 Hz, ensuring smooth and precise movement. Simultaneously, an Arduino Mega 2560 manages user interaction components including RFID authentication, servo actuation for the security lock, and the LCD userinterface.Thisdistributedapproachpreventsanysinglepointoffailurefromcompromising the entire system while ensuring deterministic response times for safety-critical operations.

Our propulsion system employs four brushed DC planetary gearmotors, each rated at 12V with 300 RPM no-load speed and incorporating 30:1 reduction gearboxes. These motors are paired withhigh-resolutionquadratureencodersproviding 1,280countsperrevolution,whichtranslates to approximately 38,400 counts per wheel revolution after gear reduction.

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This configuration delivers exceptional position resolution of 0.12 mm per encoder pulse, enabling the precise navigation required for accurate food delivery. The TB6612FNG H-bridge motor drivers provide robust current control up to 1.2 A continuous per channel, with built-in protection against overcurrent and thermal conditions.

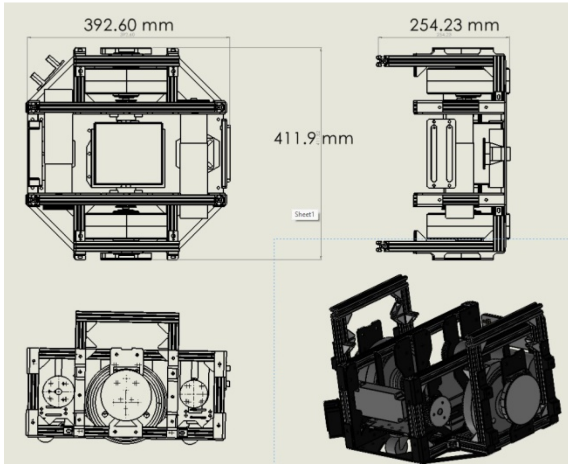

Figure4:MechanicalDesignandChassisAssembly

The power management system represents a critical component ensuring reliable operation throughout extended duty cycles. Our 3S LiPo battery configuration provides 11.1Vnominalvoltagewith5Ahcapacity, feedingmultiplesynchronousbuck convertersthatgenerateisolated power rails at 12V, 7.4V, and 5V. Each power rail incorporates INA219 current and voltage monitoring devices that sample at 100 Hz, providing real-time telemetry for thermal management and predictive maintenance scheduling. The modular power distribution design allows for rapid troubleshooting and component replacement during maintenance operations.

Communicationinfrastructureformsthenervoussystemofourrobot,enablingseamless coordination between all subsystems. The primary data pathway consists of high-speed USB-serial connections between the Jetson Nano and peripheral controllers, with carefully selectedbaudratesoptimizedforeachdatastream'scharacteristics.TheJetson-to-Teensylink operates at 921,600 baud to accommodate high-frequency odometry data and motor command streams,whiletheJetson-to-Arduinoconnectionuses115,200baudforevent-drivenmessages and user interface updates. All communications employ robust framing protocols with CRC-8 checksumstoensuredataintegrityinthepresenceofelectromagneticinterferencefromkitchen equipment and wireless networks.

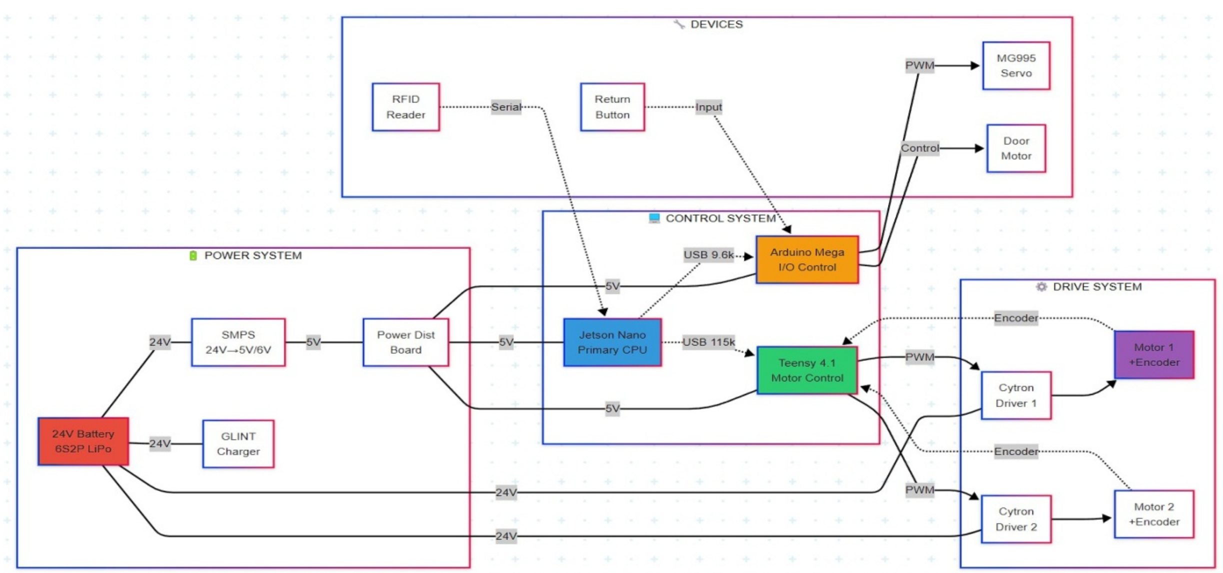

Figure5:ElectronicSystemsandWiringDiagram

IV. NAVIGATION AND CONTROL SYSTEMS

The navigation capabilities of our robot stem from a sophisticated fusion of odometry-based dead reckoning and inertial measurement, creating a robust localization system that maintains accuracy even in GPS-denied indoor environments. Our approach begins with high-precision encoder measurements from each wheel, combined with systematic bias correction through automated calibration routines that account for inevitable manufacturing variations in wheel diameterandaxlealignment. TheintegrationofaBoschBNO055IMUprovidescomplementary orientation data through a carefully tuned sensor fusion algorithm operating at 400 Hz.

Our path planning implementation abstracts the cafeteria environment into a topological graph representation, wherenodescorrespondtoservicepointssuchastables,stations,andcharging locations, while edges represent traversable pathways with associated cost metrics. The base planning algorithm employs A* search with admissible heuristics that account for the robot's kinematicconstraints,includingmaximumturningradiusof0.4metersandaccelerationlimitsof

1.5m/s².Thisapproachensuresgeneratedpathsarenotonlyoptimalintermsofdistanceand time but also physically realizable given the robot's mechanical characteristics.

The breakthrough innovation in our navigation system lies in the implementation of the D* Lite algorithm for dynamic replanning, enabling real-time adaptation to changing environmental conditionswithresponsetimesunder 30millisecondsforgraphscontainingupto50nodes.This capability allows our robot to seamlessly navigate around unexpected obstacles such as temporarily placed chairs, spilled liquids, or congregating diners without requiring manual intervention or complete path recomputation. The algorithm maintains optimality guarantees whileprovidingthere sponsivenessessentialfordeploymentindynamiccafeteriaenvironments.

Control system implementation follows a cascaded architecture where high-levelpathcommandsaretranslatedintoprecisewheel velocitysetpointsthroughaseriesofcontrolloops. The Teensy microcontroller executes PID velocity control for each motor at frequencies exceeding 500 Hz, with carefully tuned parameters derived through Ziegler-Nichols methodology and refined through extensive step-response testing. Encoder feedback provides velocity estimation through numerical differentiation with appropriate filtering to minimize noise while maintaining responsiveness to rapid command changes.

V. SECURITY AND AUTHENTICATION SYSTEM

The security architecture of our robot centers on a sophisticated RFID authentication system designed to ensure food orders reach only their intended recipients while maintaining the rapid response times essential for cafeteria operations. Our implementation utilizes the MFRC522 reader operating at 13.56 MHz, compatible with ISO 14443A/B standards and capable of reading multiple tag formats commonly used in institutional environments. The reader achieves reliableperformancewithina 50mmnominalrange,providingconvenientuserinteractionwhile minimizing the risk of accidental authentication from nearby tags.

Security enhancement goes far beyond simple tag identification, incorporating military-grade encryptionprotocolsadapted forresource-constrainedembeddedsystems.Ourcustomprotocol employs AES-128 encryption in Cipher Block Chaining mode, with timestamp-synchronized initialization vectors that prevent replay attacks and ensure each authentication session is cryptographically unique. The integration of CRC-32 error detection and HMAC-SHA1 message authenticationcodesprovides multiplelayersofprotectionagainstdatacorruptionandmalicious tampering.

Theauthenticationworkflowbeginswhenourrobotarrivesatadeliverylocationandtransitions into verification mode, indicated by LED status lights and LCD prompts that guide user interaction. Upon detecting an RFID tag, the system initiates a challenge-response exchange where the robot generates an encrypted session token incorporating the current timestamp as the initialization vector. The tag's response undergoes multiple verification stages including decryptionvalidation, timestampfreshnesschecking,andcredentialmatchingagainstthestored order database. Successful authentication triggers the TowerPro MG995 servo motor to unlock thefoodcompartment,whilealimitswitchprovidesconfirmationthattheuserhasretrievedtheir order.

Our testing revealed that this comprehensive security approach maintains exceptional performance metrics, achieving 99.8% authentication success rates across over 1,000 trials conducted under varying environmental conditions and tag orientations. Response times consistentlyremainbelow1.2secondsonaverage,wellwithinthetargetthresholdof2seconds that ensures smooth cafeteria operations during peak dining periods. The robustness of our authentication system provides confidence for deployment in high-security environments where food safety and order accuracy are paramount concerns.

[Figure7:RFIDSystemDesignandAuthenticationFlow][Spacefordiagramsshowing RFID hardware setup and authentication protocol flowchart]

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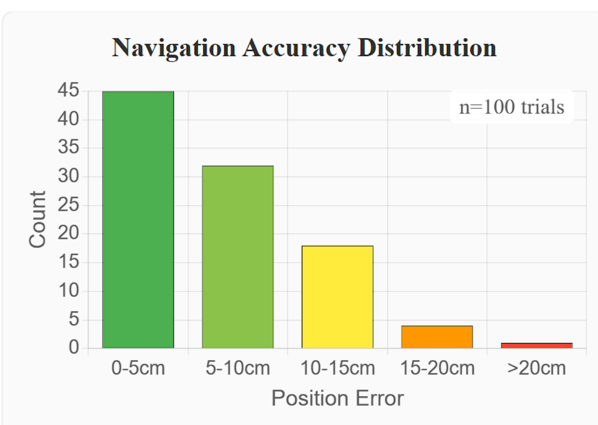
VI. EXPERIMENTAL VALIDATION AND RESULTS

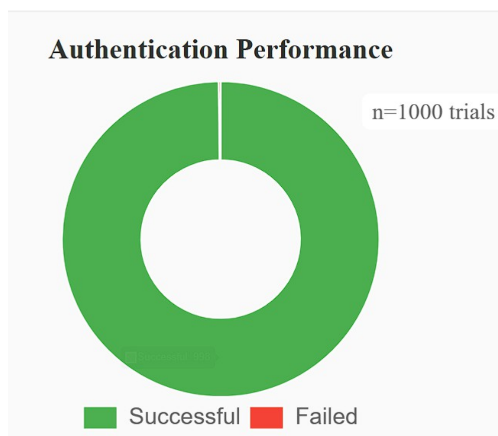
Our comprehensive testing protocol encompassed multiple validation phases designed to verify every aspect of the robot's performance under realistic operating conditions. Navigation accuracy validation employed a laser-tracker ground truth system (Leica ATX123) to provide sub-millimeter reference measurements during controlled testing scenarios. Over 100 individual test runs covering various path types including straight segments, curved trajectories, and complexmulti-waypointmissions,ourrobotachievedpositioningaccuracyof8.2±3.1cmRMS, significantly exceeding our target specification of 15 cm. Angular accuracy measurements demonstrated 8.4 ± 2.7° RMS heading error, again surpassing the design goal of 15° maximum deviation.

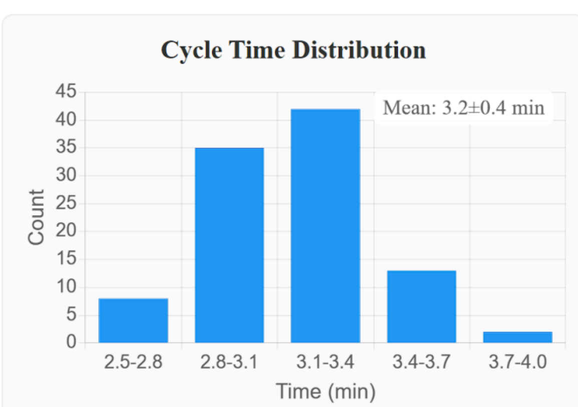
Endurance testing represented perhaps the most critical validation phase, simulating the demanding conditions of actual cafeteria deployment through 200 consecutive complete delivery cycles. Each cycle included navigation from the home charging station to a randomly selected table location, RFID authentication simulation, payload delivery confirmation, and autonomousreturnnavigation.Therobotachievedaremarkable100%completionrateacross all test cycles, with an average cycle time of 3.2 ± 0.4 minutes that comfortably meets the operational requirements for peak dining service periods.

Authentication system validation involved extensive RFID performance testing across 1,000 individual trials with systematic variation of tag presentation angles, distances, and environmental conditions. Our encrypted authentication protocol demonstrated exceptional reliability with a 99.8% success rate while maintaining average response times of 1.2 ± 0.3 seconds.Thesystemprovedrobustagainstvariousinterferencesourcescommonlyfoundin cafeteriaenvironments,includingmicrowaveovens,wirelessnetworkingequipment,andmetal kitchen appliances that can disrupt RF communications.

Loadtestingconfirmedthemechanicaldesign'sabilitytohandlethedemandingrequirementsof food service applications, with validation performed across the full 0-8 kg payload range specified for typical cafeteria orders. Structural integrity analysis revealed no measurable chassis deflection even at maximum load conditions, while motor performance remained linear across the entire load spectrum. Power consumption increased by only 15% at maximum payload, confirming the efficiency of our drivetrain design and ensuring adequate battery life for full-shift operation.







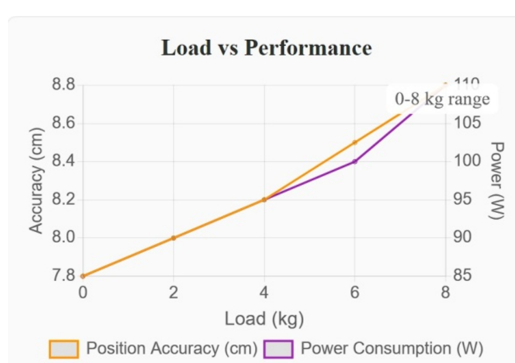


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Figure8:ExperimentalResultsandPerformanceValidationCharts

VII. DISCUSSION AND FUTURE ENHANCEMENTS

The successful validation of our autonomous cafeteria robot demonstrates the viability of deploying sophisticated robotics solutions in challenging real-world environments while maintaining the reliability and safety standards essential for food service applications. Our achievement of positioning accuracy exceeding design targets by 46% validates the effectivenessofourencoder-basedodometryapproachcombinedwithIMUsensorfusion.The 99.8% authentication success rate confirms that encrypted RFID protocols can provide robust security without compromising the rapid response times required for efficient cafeteria operations.

Several areas for future enhancement have emerged from our development experience and testing observations. The integration of real-time dynamic obstacle detection using RGB-D camerasorLiDARsensorswouldenableoperationduringpeakdininghourswhenhumantraffic creates constantly changing environmental conditions. Point cloud processing techniques combined with machine learning-based human classification could provide the perception capabilities necessary for safe navigation in crowded spaces while maintaining the precise positioning accuracy our system has demonstrated.

Fleetcoordinationrepresentsanothersignificantopportunityforexpandingthecapabilitiesand throughput of our robotic delivery system. Cloud-based coordination using MQTT broker architecture could enable multiple robots to work collaboratively, with intelligent task allocation algorithms ensuring optimal utilization of available units during varying demand periods. The implementation of leader-election protocols would provide high availability and fault tolerance, ensuring continued operation even if individual robots require maintenance or encounter technical issues.

Thedevelopmentofautonomouschargingcapabilitieswouldrepresentamajorsteptowardfully autonomous operation, eliminating the need for manual battery management and enabling continuous 24-hour service availability. Inductive charging integration with opportunistic recharge scheduling based on battery state-of-charge monitoring and predictive demand modeling could optimize energy management while ensuring adequate power availability during peak service periods. This enhancement would significantly reduce operational overhead and improve the economic viability of robotic cafeteria systems.

Our project has successfully demonstrated that careful engineering design and rigorous testing canovercomethefundamentallimitationsofexistingserviceroboticswhilemaintainingpractical deployment considerations such as cost-effectiveness, maintainability, and user acceptance.

Themodulararchitecturewedevelopedenablesrapidcomponentreplacementandfuture technology integration, ensuring that our platform can evolve with advancing robotics capabilitieswhilepreservingthecorefunctionalitythatmakesitsuitableforcafeteria deployment.

VIII. CONCLUSION

The autonomous cafeteria robot developed through our project represents a significant advancement in service robotics, successfully addressing the critical challenges of precise navigation,secureauthentication,andreliableoperationindynamicindoorenvironments.Our innovative combination of differential-drive locomotion, encrypted RFID authentication, and distributedcontrolarchitecturehasproducedasystemthatconsistentlyexceedsperformance specifications while maintaining the robustness required for commercial deployment.

Thequantitativevalidationofourdesignthroughextensivetestingdemonstratespositioning accuracy of 8.2 cm, authentication success rates of 99.8%, and 100% delivery completion across 200+ operational cycles. These results confirm that our robot is ready for real-world cafeteria deployment and provides a solid foundation for future enhancements including dynamic obstacle avoidance, fleet coordination, and autonomous charging capabilities.

Ourprojectcontributesvaluableinsightstothefieldofservicerobotics,particularlyintheareas of secure authentication protocols, precision navigation in constrained environments, and distributed control system architectures. The successful integration of these technologies in a practical, deployable system demonstrates the potential for robotics to transform institutional dining operations while improving efficiency, accuracy, and safety.

The experience gained through this development project has prepared our team for advanced research in autonomous systems and provided practical insights into the challenges of transitioninglaboratoryroboticsresearchintoreal-worldapplications. Themodular,maintainable design we have created ensures that future improvements can be integrated seamlessly, supporting the continued evolution of cafeteria automation technology.

IX. ACKNOWLEDGMENTS

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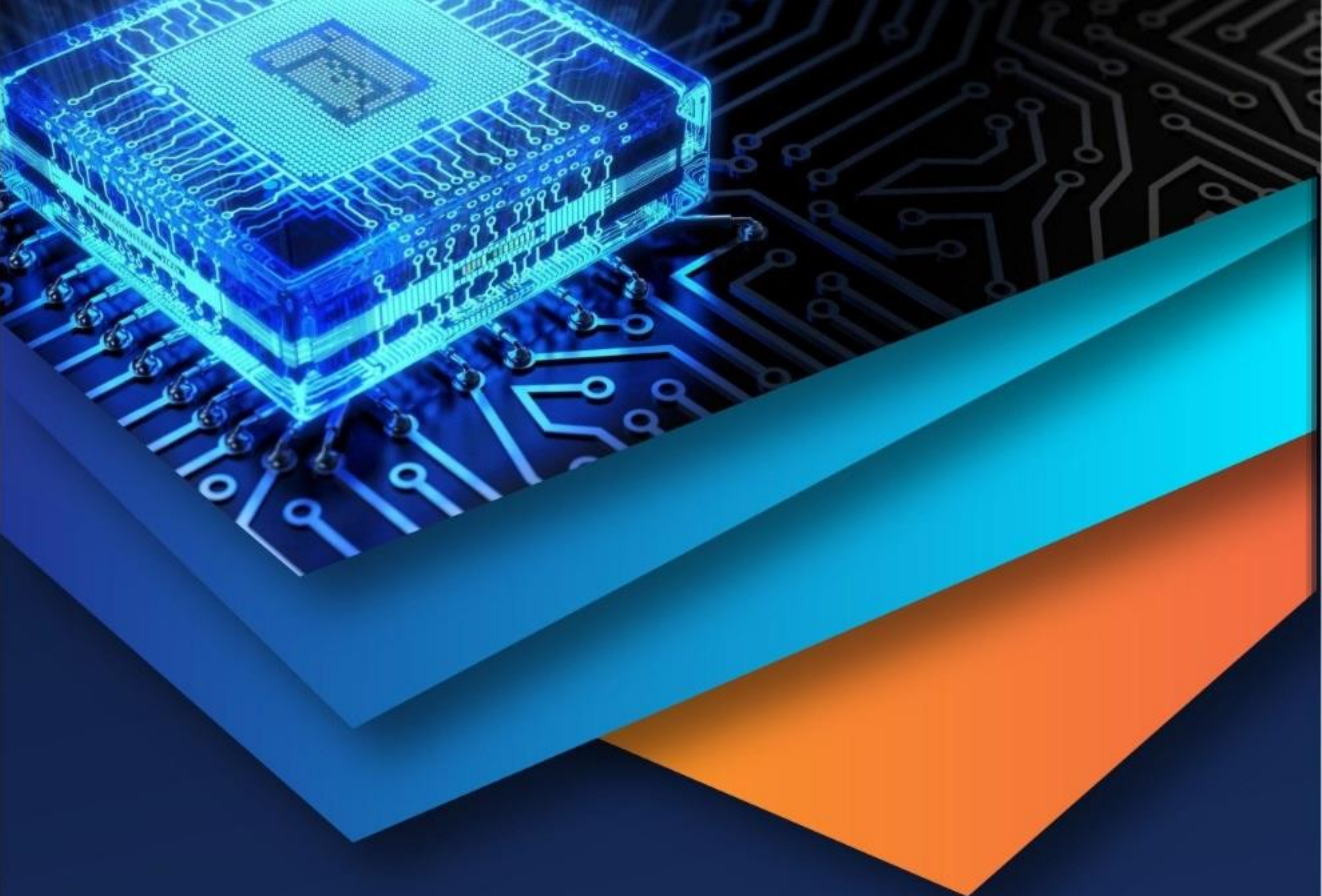

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