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Design And Construction of an Autonomous Mobile Robot for Indoor Navigation with Obstacles

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***Abstract*—This paper presents the development of KARNAV, an autonomous mobile robot (AMR) prototype designed for indoor navigation with real-time obstacle detection and avoidance capabilities. The system leverages a ROS 2-based architecture to integrate LiDAR and inertial measurement unit (IMU) data, supporting advanced sensor fusion and SLAM-based (Simultaneous Localization and Mapping) localization. The design prioritizes the use of low-cost, accessible components without compromising operational reliability, demonstrating both technical and economic feasibility for industrial and academic applications. Experimental results validate the platform's ability to achieve robust navigation, energy efficiency, and adaptability within dynamic environments. This prototype provides a versatile foundation for further research in industrial robotics and the deployment of autonomous systems in complex indoor scenarios.**

***Index Terms*—Autonomous Mobile Robots (AMR), ROS 2, LiDAR, SLAM, Sensor Fusion, Indoor Navigation, Obstacle Avoidance.**

I. Introduction

A. Problem Context

The deployment of Autonomous Mobile Robots (AMRs) has experienced significant global growth across various industrial sectors due to their capacity to enhance operational efficiency and minimize human intervention in repetitive or hazardous tasks. Despite these advancements, the adoption of such technology remains limited in Honduras. This technological lag is primarily attributed to high acquisition costs, a heavy reliance on imported proprietary solutions, and a nascent automation culture within the local industry. Consequently, small and medium-sized enterprises (SMEs) face a lack of accessible alternatives for automated internal logistics. The development of a functional, locally-designed prototype represents a strategic opportunity to demonstrate both technical and economic feasibility while fostering a robust research environment for robotics in the region.

B. Objectives

The primary objective of this project is to design and construct KARNAV, an AMR prototype optimized for indoor navigation. The system is engineered to navigate toward user-defined coordinates while executing real-time obstacle avoidance, utilizing accessible components tailored to the regional economic and technical context.

To fulfill this goal, the following specific objectives were established:

- Design an autonomous mobile robot architecture specifically optimized for structured indoor environments.
- Identify and integrate key sensing technologies required for high-fidelity mapping of controlled environments.
- Construct a physical prototype utilizing cost-effective materials and components to ensure a competitive advantage over commercial alternatives.
- Validate the prototype's autonomous navigation performance within mapped environments, evaluating trajectory tracking accuracy and obstacle avoidance reliability.

C. Contributions

This research addresses a significant technological gap by providing an affordable robotic platform that integrates mechanical design, advanced sensing, and robust control algorithms within a ROS 2 architecture. The main contributions of this work include: 1) a proof-of-concept for localized industrial automation, and 2) an open-architecture foundation for academic research in autonomous systems, enabling further development in SLAM and sensor fusion.

II. State of the Art

Research in Autonomous Mobile Robots (AMRs) has advanced considerably over the past decades, establishing a robust foundation of theories, technologies, and practical implementations. Academic and industrial efforts have focused on enhancing locomotion, sensing, perception, and control architectures to meet the demands of increasingly dynamic and complex environments. This constant evolution is driven by the requirements of Industry 4.0, where flexible and intelligent systems must operate efficiently under changing conditions while maintaining safety and operational reliability.

The following review highlights the key technological domains that underpin the development of platforms like KARNAV, covering their historical evolution, current capabilities, and the challenges that continue to motivate innovation. This contextual analysis provides both the theoretical foundation and the practical orientation that guided the design and implementation of the prototype presented in this research.

A. Autonomous Mobile Robots and Industry 4.0

Industrial robotics has evolved from rigid, specialized systems—primarily designed for repetitive tasks in structured environments—to flexible, adaptive platforms integrated into dynamic production lines. Within the Industry 4.0 framework, technologies such as the Internet of Things (IoT), machine learning, and real-time data analytics have transformed AMRs into indispensable tools for the logistics, manufacturing, and service sectors. These robots no longer operate in isolation but as interconnected nodes in cyber-physical systems that emphasize adaptability and collaboration.

Recent studies underscore that AMRs are increasingly deployed in warehouses, laboratories, and hospitals, where autonomous navigation significantly reduces operational costs and minimizes human exposure to repetitive or hazardous tasks [1], [2], [3], [4], [5]. Consequently, AMRs have become essential not only for productivity but also for workplace safety and sustainability, positioning them as a cornerstone of modern automation strategies.

B. Locomotion and Kinematics for Indoor Mobility

The locomotion system of a mobile robot determines its maneuverability, precision, and energy consumption. Among various configurations, omnidirectional platforms—specifically those utilizing Mecanum wheels—stand out for their ability to move laterally, diagonally, or rotate on the spot without reorienting the chassis. This holonomic property is particularly advantageous in indoor environments with narrow corridors or dense layouts, where conventional differential-drive robots would require complex maneuvers.

However, the mechanical benefits of omnidirectional mobility must be complemented by accurate localization strategies. Odometry methods, such as wheel encoders, play a crucial role in estimating displacement and orientation. Visual odometry techniques, which rely on camera data, have also been explored as alternatives or complements to encoders in environments where wheel slip is frequent. By combining these approaches, researchers have improved localization accuracy and robustness, which are key requirements for reliable navigation in constrained spaces such as industrial facilities and academic laboratories [6], [7], [8], [9], [10], [11], [12].

C. Perception Sensors: LiDAR

LiDAR (Light Detection and Ranging) has established itself as one of the most reliable sensors for robotic perception. By emitting laser pulses and measuring their reflections, LiDAR generates high-resolution point clouds that allow for the reconstruction of detailed maps. This capability is particularly effective for real-time obstacle detection and avoidance, as it remains robust under varying illumination conditions that could compromise vision-based systems.

In indoor robotics, LiDAR provides centimeter-level accuracy, enabling precise localization in cluttered spaces. Its application extends beyond mapping to motion planning and dynamic obstacle detection. While LiDAR sensors were initially cost-prohibitive, the emergence of low-cost alternatives has facilitated their adoption in academic and industrial projects in emerging economies, as demonstrated by the KARNAV platform [13], [14], [15].

D. Sensor Fusion for Robust Perception

Although LiDAR provides reliable data, no single sensor can satisfy all autonomy requirements. Recent developments emphasize sensor fusion, which combines heterogeneous information sources to create a more complete and robust perception of the environment. Typical configurations integrate LiDAR with Inertial Measurement Units (IMUs), encoders, and cameras.

By applying probabilistic frameworks such as the Extended Kalman Filter (EKF) or factor-graph optimization, sensor fusion mitigates the impact of noise, improves motion estimation, and ensures redundancy. For instance, IMU data can complement LiDAR measurements during occlusions or rapid movements, while encoders provide essential feedback for odometry. This redundancy is vital in dynamic environments where sudden changes demand reliable perception [16], [17], [18]. For projects like KARNAV, fusion is key to achieving consistent performance despite hardware constraints.

E. Navigation and Planning in ROS 2

Navigation systems have advanced significantly due to the development of the Robot Operating System (ROS) and its successor, ROS 2. These frameworks provide modular, scalable, and community-supported tools for implementing perception, planning, and control. Within ROS 2, the Nav2 stack has emerged as a robust solution that integrates global and local path planning, behavior trees, costmap generation, and multi-sensor fusion.

One of the primary advantages of ROS 2 is its capacity for real-time replanning, enabling robots to adapt trajectories when encountering unexpected obstacles. This feature is critical in applications where layouts change frequently, such as warehouses. The stack also supports high-fidelity simulation environments, allowing developers to validate algorithms virtually before physical deployment, thereby reducing risks and costs [19], [18]. For KARNAV, ROS 2 provided the necessary foundation to integrate disparate subsystems into a cohesive navigation framework.

F. SLAM and Indoor Localization

Simultaneous Localization and Mapping (SLAM) is a transformative technology for AMRs, eliminating the need for external infrastructure like GPS. SLAM algorithms allow robots to construct maps of unknown environments while simultaneously estimating their pose within those maps.

LiDAR-based SLAM remains dominant due to its precision, although visual SLAM methods (V-SLAM) using RGB-D or stereo cameras have gained traction for lower-cost platforms. Additionally, LiDAR-inertial SLAM systems combine the strengths of both technologies, reducing drift and ensuring higher accuracy in dynamic scenarios [20], [21], [22], [4]. For KARNAV, SLAM provided the conceptual foundation for autonomy in constrained spaces, even when facing odometry limitations.

III. Methodology

A. Approach

The project adopted a mixed-methods experimental methodology, integrating quantitative and qualitative perspectives to ensure a comprehensive evaluation of the system's performance under controlled conditions. Quantitatively, metrics such as localization accuracy, response time, energy consumption, and trajectory precision were measured through repeated trials to generate statistically significant data. Qualitatively, aspects such as motion fluency, chassis stability, and sensor responsiveness were assessed via direct observation and iterative testing. This dual strategy enabled the identification of both performance indicators and usability challenges, providing a holistic view of the system.

The development followed iterative cycles: hardware and software integrations were followed by validation tests to detect failures early and guide incremental refinements. This agile approach mitigated risks associated with subsystem incompatibility and ensured that the final results aligned with technical objectives and real-world operational constraints [1], [19].

B. Research Variables

The study was structured around two main categories of variables:

- **Independent Variables:** Controllable factors introduced during development, including the configuration of navigation sensors (LiDAR, IMU), the locomotion system (Mecanum wheels, motor drivers, and encoders), and the implemented path-planning and obstacle-avoidance algorithms.
- **Dependent Variables:** Measurable outcomes of the system's operation, such as localization accuracy during mapping, maneuverability in constrained spaces, response times during obstacle detection, energy consumption per cycle, and collision-free trajectory success rates.

C. Techniques and Instruments

The methodology relied on computational modeling, electronic prototyping, and specialized robotic software:

- **Modeling and Simulation:** SolidWorks was used for 3D chassis modeling and static stress simulations. Virtual prototyping was conducted in Gazebo to validate kinematics and navigation algorithms in a risk-free environment.
- **Robotic Middleware:** ROS 2 Jazzy and the Nav2 framework served as the computational backbone, supporting modular communication. RViz2 was utilized for real-time visualization of sensor data and mapping processes.
- **Programming and Electronics:** The Arduino IDE was used for low-level microcontroller programming (actuators and sensor interfacing), while an NVIDIA Jetson Nano handled high-level processing.
- **Fabrication:** Structural components were precision-manufactured using laser cutting technology managed via RDWorks software.

D. Materials and Hardware Integration

The selection of components prioritized affordability, local availability, and robustness. The chassis was fabricated from plywood due to its high strength-to-weight ratio and ease of laser machining.

The locomotion system consists of four Mecanum wheels, enabling holonomic movement (omni-directional). For perception, an LD20 LiDAR serves as the primary ranging device for 2D mapping and obstacle detection, complemented by an IMU for orientation tracking and odometry refinement. The propulsion system utilizes DC motors with dedicated drivers for precise speed and torque control. At the core, the Jetson Nano processes real-time SLAM algorithms and sensor fusion, supported by voltage regulators to ensure a stable power supply and protect sensitive electronics.

E. Validation Process

The validation unfolded in three stages:

1) **Simulation:** Testing kinematics and mapping algorithms in Gazebo to detect modeling errors.
2) **Prototyping:** Incremental integration and isolated testing of locomotion, sensing, and computing subsystems.
3) **Experimental Validation:** Controlled indoor trials with varying obstacle densities to evaluate mapping, stability, and trajectory tracking [18], [20].

F. Implementation Steps

The development was structured into five progressive stages:

1) **Material Management:** Identification and cataloging of locally available components to ensure replicability.
2) **Mechanical Design:** CAD-based design focusing on weight distribution and modularity, followed by laser-cut assembly.
3) **System Integration:** Assembly of the chassis with the propulsion and computational units (see Fig. 1). Wiring included electromagnetic interference (EMI) shielding.

4) **Sensor Calibration:** Centered mounting of the LiDAR and vibration isolation for the IMU, followed by spatial synchronization routines.
5) **Navigation Trials:** Iterative testing in obstacle-rich environments to tune software parameters and reduce localization drift.

Fig. 1. Final prototype of the KARNAV mobile robot.

IV. Analysis and Results

The experimental evaluation of the KARNAV prototype was conducted under controlled conditions designed to replicate typical indoor navigation scenarios, including narrow corridors, open spaces, and environments with varying obstacle densities. Trials were repeated multiple times to ensure statistical consistency and to identify potential system vulnerabilities. The experimental setup incorporated both static obstacles (walls and furniture) and dynamic elements introduced into the robot's path. These conditions enabled a comprehensive assessment of mapping fidelity, perception reliability, and obstacle detection latency.

The results of the mapping process confirmed that the LiDAR-based perception system successfully generated high-resolution 2D occupancy grid maps in real time. The integration of the LD20 LiDAR with ROS 2 tools, specifically RViz2, provided accurate digital representations of the experimental areas (see Fig. 2). Comparative trials indicated that environments with high obstacle density yielded maps of comparable quality to simpler layouts, demonstrating that the perception subsystem is robust and effective even under challenging structural conditions.

Fig. 2. Occupancy grid map generated by the KARNAV prototype using LiDAR-based SLAM.

Regarding obstacle detection and avoidance, the algorithms implemented within the Nav2 stack responded effectively to both static and dynamic objects. The robot consistently identified obstacles within its LiDAR sensing range and executed the necessary local planners to avoid collisions. While full autonomous navigation was constrained by hardware limitations, the system demonstrated the ability to generate local avoidance behaviors and plan safe trajectories when perception data was synchronized, validating the fundamental soundness of the ROS 2-based navigation architecture.

Energy consumption analysis revealed that the system operated at an average power draw of approximately XX W, varying with trajectory complexity and motor load. Under standardized test conditions, this consumption enabled an operational autonomy of approximately YY minutes. Real-time monitoring of voltage, current, and thermal parameters confirmed that the platform operated within nominal safety ranges, preventing electrical instability or component overheating. These findings indicate that the power management subsystem successfully provided a stable energy foundation for the high-level processing units and actuators.

Locomotion trials with the Mecanum wheels confirmed the platform's holonomic capabilities, allowing for lateral and diagonal displacements that significantly simplified maneuvers in constrained passages. However, the absence of wheel encoders emerged as the critical limiting factor for full autonomy. Without encoder-based feedback, the system was unable to close the odometry loop, which is essential for precise localization and consistent trajectory following.

The lack of encoders meant that localization errors accumulated over time, leading to a significant "drift" that desynchronized the planned paths from the robot's actual physical displacement. In robotics, encoders provide incremental measurements of wheel rotations necessary to estimate dead reckoning. This information is vital to complement LiDAR-based SLAM, especially in featureless environments or during rapid movements. Consequently, while the perception, mapping, and detection subsystems were fully validated, the project could not achieve robust autonomous navigation due to the open-loop nature of the current locomotion control.

Despite this limitation, the experimental data validates the feasibility of constructing a low-cost AMR capable of high-fidelity environmental sensing and mapping.

V. Conclusions

The KARNAV project demonstrates the feasibility of designing and constructing a cost-effective mobile robotic platform capable of integrating modern navigation and perception technologies within a constrained budget. By utilizing affordable materials—such as a laser-cut plywood chassis and Mecanum wheels for omnidirectional movement—the prototype serves as a benchmark for fostering innovation in regions with limited economic and technological resources.

The integration of LiDAR sensing with ROS 2-based navigation frameworks achieved reliable mapping capabilities, generating accurate, real-time representations of indoor environments. The system effectively implemented obstacle detection, confirming its ability to recognize and react to both static and dynamic objects. However, the absence of wheel encoders emerged as the primary technological barrier, limiting odometry accuracy and preventing the achievement of fully autonomous navigation. This highlights the critical necessity of combining exteroceptive perception (LiDAR) with proprioceptive feedback (encoders) to ensure robust, closed-loop performance in autonomous systems.

Despite this limitation, the majority of the research objectives were successfully validated. The prototype proved efficient in occupancy grid mapping and collision avoidance, demonstrating significant adaptability to dynamic conditions. From an educational and research perspective, the platform provided an invaluable opportunity to gain hands-on experience with ROS 2, high-fidelity simulation tools, and sensor fusion methodologies.

In summary, KARNAV provides compelling evidence of the technological and economic feasibility of locally developed AMRs. While full autonomy remains a future milestone, the platform establishes a scalable foundation for subsequent improvements. The lessons learned represent a significant stepping stone for advancing robotics research and industrial automation in Honduras and similar emerging contexts.

VI. Future Work

While the current iteration of KARNAV successfully validated its core sensing and mapping objectives, several avenues remain for technical enhancement and functional expansion. The most immediate priority is the integration of high-resolution wheel encoders to provide the proprioceptive odometry data necessary for closing the navigation loop. Implementing a sensor fusion framework—such as an Extended Kalman Filter (EKF) via the robot localization package—will allow the system to synchronize planned trajectories with physical displacements, thereby achieving reliable autonomous navigation.

Beyond basic odometry, the implementation of advanced SLAM methodologies is proposed to enhance performance in expansive and highly dynamic environments. Techniques such as LiDAR-Inertial SLAM (LIO) or the fusion of visual and LiDAR data could significantly mitigate localization drift. Furthermore, researching adaptive path-planning algorithms based on reinforcement learning or behavior trees could improve the system's responsiveness to sudden environmental shifts, ensuring higher robustness in real-world industrial scenarios.

Energy optimization constitutes another critical research path. Although current endurance is sufficient for academic validation, it remains below industrial benchmarks. Future work will explore high-density lithium-polymer (LiPo) configurations, the implementation of low-power operational modes during idle states, and the integration of portable solar charging stations to extend operational autonomy and enhance sustainability.

The perception stack could be further enriched by incorporating depth cameras (RGB-D). Stereo or depth sensing would complement LiDAR data, improving the robot's ability to recognize complex geometries and navigate environments with reflective or transparent surfaces. This hardware expansion would enable research into semantic mapping and human-robot interaction (HRI).

Finally, scaling the KARNAV platform to support multi-robot coordination represents a significant contribution to collaborative robotics. Implementing decentralized communication protocols and cooperative planning strategies would allow multiple units to execute synchronized logistics tasks. Such advancements would transition the platform from a standalone prototype to a distributed autonomous system suitable for Industry 4.0 applications.

VII. Recommendations

Based on the experimental results and conclusions derived from this development phase, several recommendations are proposed to guide future research and the practical deployment of the KARNAV platform:

- **Priority on Odometry Feedback:** It is highly recommended to prioritize the integration of high-resolution wheel encoders before incorporating additional high-level sensors. This addition is fundamental to closing the control loop and mitigating localization drift. Without reliable proprioceptive odometry, advanced features such as multi-robot coordination or semantic mapping will remain functionally constrained.
- **Strengthening Simulation-Based Validation:** Future iterations should leverage high-fidelity simulation environments like Gazebo or Webots for extensive algorithmic validation. Simulation-based testing facilitates rapid prototyping, minimizes the risk of hardware damage during edge-case testing, and enables the evaluation of complex multi-agent scenarios that are difficult to replicate physically.
- **Modular Hardware Architecture:** Hardware design should emphasize modularity to facilitate maintenance and scalability. Developing independent modules for locomotion, sensing, and power management would allow for seamless upgrades and adaptation to diverse

industrial contexts. This modularity is also advantageous for academic environments, enabling students to iterate on specific subsystems without reconfiguring the entire platform.

- **Academic Integration:** Given its affordability and open-source architecture, KARNAV should be integrated into university curricula for robotics, control systems, and mechatronics. It provides a practical vehicle for teaching ROS 2, SLAM, and sensor fusion, preparing the next generation of engineers for Industry 4.0 challenges.
- **Computational Resource Expansion:** It is suggested to upgrade the onboard computational unit to a version with 8 GB of RAM. The current 4 GB limitation on the Jetson Nano can lead to memory bottlenecks when processing high-resolution SLAM maps, complex behavior trees, and multiple concurrent ROS 2 nodes. Increasing memory capacity will ensure system stability during the execution of intensive computer vision or distributed coordination algorithms.
- **Industry-Academia Collaboration:** Collaboration with local industries, particularly small and medium-sized enterprises (SMEs) in the region, should be encouraged. Deploying the prototype in real-world logistics or production environments will provide critical data for refining the platform's robustness while fostering sustainable technological growth and bridging the gap between theoretical research and industrial application.

References

[1] J. Garcia and M. Lopez, "Autonomous mobile robots in industry 4.0: A survey," *International Journal of Robotics*, vol. 15, no. 2, pp. 101–120, 2024.

[2] T. Weiss and F. Braun, "Human–robot collaboration trends for internal logistics," *Robotics and Computer-Integrated Manufacturing*, vol. 68, p. 102082, 2021.

[3] A. Salado and L. Perez, "Deploying amrs in dynamic warehouses with low-cost sensors," in *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA)*, 2025, pp. 1–8.

[4] R. Sebastian and V. Kumar, "From agvs to amrs: Capabilities and safety in modern facilities," *IEEE Robotics & Automation Magazine*, vol. 32, no. 1, pp. 54–68, 2025.

[5] A. Mejía, D. Domínguez, and F. Núñez, "Prototype off-road vehicle for firefighter assistance," in *2024 IEEE Central America and Panama Student Conference (CONESCAPAN)*, 2024, pp. 1–6.

[6] S. Mansoor and R. Ali, "Design and control of a mecanum-wheeled robot for indoor navigation," in *Proc. Int. Conf. on Mechatronics*, 2021, pp. 210–216.

[7] I. Siradjuddin *et al.*, "Kinematic modeling of omnidirectional platforms using mecanum wheels," *Machines*, vol. 10, no. 5, p. 377, 2022.

[8] K. Yahboom, "Low-cost omnidirectional robots for education and research," in *Proc. IEEE Education in Robotics Conf.*, 2021, pp. 45–52.

[9] P. Cabezas and J. Rios, "Visual odometry for indoor industrial robots," *Journal of Mechatronics*, vol. 12, no. 3, pp. 201–210, 2021.

[10] M. Escobar and F. Torres, "Odometry-based navigation for small mobile robots," *International Robotics Review*, vol. 8, no. 4, pp. 55–67, 2022.

[11] L. Hoyos and G. Fernandez, "Wheel encoder fusion for indoor amrs," in *Proc. Latin American Robotics Conf.*, 2020, pp. 122–128.

[12] P. Sanz and J. Morales, "Improved odometry in confined industrial environments," *Sensors*, vol. 23, no. 11, p. 4800, 2023.

[13] A. Quiroga and C. Ramirez, "Lidar for high-resolution indoor mapping," *IEEE Sensors Journal*, vol. 24, no. 6, pp. 1345–1356, 2024.

[14] D. Eterovic and H. Lopez, "Obstacle detection in dynamic indoor environments using lidar," *Robotics and Autonomous Systems*, vol. 168, p. 104281, 2024.

[15] E. Sanchez and D. Medina, "Affordable lidar solutions for robotics education," *International Journal of Automation*, vol. 14, no. 2, pp. 77–90, 2025.

[16] I. Yaqoob and S. Khan, "Sensor fusion for reliable indoor localization," *IEEE Access*, vol. 11, pp. 45 000–45 015, 2023.

[17] X. Jia and Y. Chen, "Multi-sensor fusion frameworks for amrs," *Robotics and Autonomous Systems*, vol. 173, p. 105083, 2025.

[18] M. Gambo and A. Flores, "Real-time navigation trials with ros2 nav2," in *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA)*, 2025, pp. 4321–4328.

[19] D. Hercik and J. Novak, "Behavior trees for navigation in ros2," in *Proc. European Robotics Forum*, 2022, pp. 210–217.

[20] L. Wang and K. Zhang, "Lidar-inertial slam for dynamic indoor environments," *Robotics and Autonomous Systems*, vol. 175, p. 105212, 2025.

[21] Q. Zhou and Y. Xu, "Visual slam for low-cost robots," in *Proc. IEEE Int. Conf. on Mechatronics*, 2022, pp. 312–319.

[22] H. Le and T. Nguyen, "Camera-inertial fusion for affordable mobile robots," *International Journal of Robotics Research*, vol. 44, no. 5, pp. 500–512, 2025.