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Development Of Vision-Guided Pallet Engagement System

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Abstract

In recent years, the rapid advancement of automation technologies has significantly transformed industrial material handling systems, reducing human dependency while improving efficiency and safety. This paper presents a compact autonomous pallet docking system designed for intelligent warehouse applications. The proposed system utilizes a pre-mapped environment generated using LiDAR-based SLAM and operates using the ROS 2 framework. The robot autonomously navigates from a predefined home position, detects pallets using April Tag-based vision, and performs precise docking through centroid estimation. A scissor lift mechanism integrated with limit switch feedback ensures controlled pallet lifting, while an ultrasonic sensor enhances obstacle avoidance during load transportation. The system dynamically switches sensing strategies to ensure safe operation during both docking and undocking operations. The complete workflow from navigation to pallet docking is implemented and validated in a real-time environment. The proposed system demonstrates a cost-effective and scalable approach for autonomous pallet handling in smart industrial environments.

Keywords: *ROS 2, Autonomous Mobile Robot, SLAM, April Tag, Pallet Docking, Obstacle Avoidance, Scissor Mechanism*

1. Introduction

The increasing demand for automation in industrial environments has accelerated the adoption of intelligent robotic systems for material handling. Traditional pallet transportation methods rely heavily on human labor, resulting in inefficiencies, increased operational costs, and potential safety risks. Autonomous Mobile Robots (AMRs) provide an effective solution by enabling flexible, efficient, and safe logistics operations. In modern warehouse systems, pallet handling is a critical task that requires accurate navigation, object detection, and manipulation[1]. While industrial systems exist, they are often expensive and complex, making them unsuitable for educational and small-scale research applications. This paper proposes a compact autonomous pallet docking system that integrates navigation, perception, and mechanical handling within a single platform. The system is designed to operate in a mapped indoor environment using ROS 2 and LiDAR-based SLAM. Vision-based April Tag detection is employed for accurate pallet localization, and a scissor lift mechanism is used for pallet handling. The primary contribution of this work lies in the integration of multiple subsystems, including LiDAR-based navigation, vision-based detection, sensor-based feedback control, and mechanical lifting, into a unified and scalable solution[2].

2. System Design & Implementation

2.1. System Overview

The proposed system is an autonomous pallet docking robot designed to operate in a structured indoor environment. The platform integrates navigation, perception, and mechanical handling within a unified ROS 2 framework. Operation is based on a pre-mapped workspace where key positions — home, pallet pickup location, and pallet drop-off location are predefined. The robot executes tasks in a fixed sequence: autonomous navigation, pallet detection, April tag detection, docking, transportation, undocking and obstacle avoidance.[3]

2.2.Design and Integration

The mobile robot is equipped with an RPLiDAR C1 for environment mapping and navigation, a camera module for vision-based pallet detection, three limit switches for docking and ensure correct feedback mechanism, and an ultrasonic sensor for obstacle avoidance during loaded transport. All components are integrated through ROS 2, enabling structured communication between the navigation, perception, and control modules. Navigation relies on LiDAR-based localization and path planning[3]. The vision module detects April Tags mounted on the pallet stringers for precise alignment. Vertical pallet handling is achieved through a scissor lift mechanism driven by a horizontal lead screw[4].

2.3.Robot Base

The robot uses a differential drive configuration, which is well-suited for indoor environments due to its mechanical simplicity and precise turning capability[5]. This configuration enables the robot to manoeuvre accurately in constrained spaces and perform repeatable docking operations Figure 1. The compact form factor further supports precise alignment during fork insertion[6].

Figure 1.Robot Design

2.4.Navigation System

The navigation system is built on the ROS 2 Navigation Stack (Nav2)[7]. Localization is performed using Adaptive Monte Carlo Localization (AMCL), which estimates the robot's pose by combining LiDAR scan data with odometry from wheel encoders. The encoder data is first filtered using an Extended Kalman Filter (EKF) to reduce noise before being passed to the navigation stack. Global path planning uses the NavFn planner based on Dijkstra's algorithm, while the D* algorithm handles replanning when the environment changes Figure 2. Local motion is controlled by the Dynamic Window Approach (DWB) controller, which selects safe velocity commands in real time[8]. Obstacle management is handled through layered global and local costmaps with inflation margins. Recovery behaviors and a velocity smoothing module ensure stable and reliable operation throughout navigation[9].

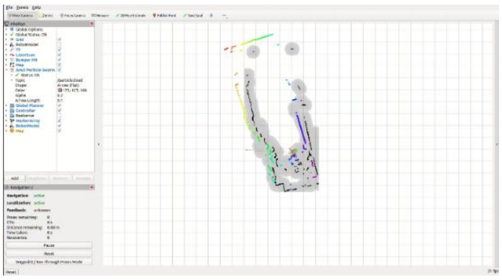

Figure 2 Localization Using Nav2 Param

2.5.Vision System

A camera module is integrated into the robot to detect AprilTags mounted on the pallet stringers Figure 3. These tags are permanently stamped in metal rather than printed, ensuring durability against wear, moisture, and lighting variations over time[10]. The camera continuously captures image frames, which are processed using an April Tag detection algorithm Figure 5. The algorithm identifies the tag by detecting its unique square pattern and extracts key feature points (corners)[11]. Using these features, the system performs 3D pose estimation, computing the position and orientation of the tag relative to the camera frame. The estimated pose provides six degrees of freedom (6-DoF): three for position (x, y, z) and three for orientation (roll, pitch, yaw). This information is transformed into the robot's coordinate frame using calibration parameters between the camera and the robot base[12]. Based on the computed pose, the robot aligns itself with the pallet by minimizing positional and angular error Figure 4. The centroid of multiple detected tags can be used to improve alignment accuracy and robustness. Once alignment is achieved, the robot performs precise docking by inserting its forks into the pallet slots. In addition to localization, April Tags can encode information such as pallet ID, category, and destination[13]. This

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enables higher-level decision-making within the system, allowing the robot to autonomously select tasks and routes[14].

Figure 3 **Centroid Estimation For April Tag**

2.6.Pallet Design

The pallet is modified from the standard three-stringer configuration to a two-stringer design. This simplification reduces alignment complexity and allows the fork to be inserted more accurately during docking Figure 7. The reduced stringer count also decreases the total weight, which is beneficial for compact robotic platforms with limited payload capacity[15].

2.7.Lifting Mechanism

A scissor mechanism driven by a horizontal lead screw provides controlled vertical motion for pallet handling. Unlike conventional forklifts where the forks themselves ascend, this design keeps the fork fixed while the scissor structure raises the pallet. This approach improves load stability and reduces the vertical space requirement, making it more appropriate for small-scale platforms[16].

2.8.Feedback Mechanism

Three limit switches provide positional feedback across the docking and lifting cycle:

- Switch 1: Mounted on the robot body. Triggered when the pallet contacts the frame, confirming fork insertion.
- Switch 2: Positioned at the upper end of the scissor travel. Triggered when the pallet reaches full transport height, signaling the robot to begin moving.
- Switch 3: Positioned at the lower end. Triggered when the pallet is fully lowered at the goal location, confirming unloading is complete[17].

This sequence ensures each phase is verified before the next begins, eliminating reliance on open-loop timing Figure 6.

2.9 Web-Based Monitoring and Control Interface

A web-based GUI is developed for remote monitoring and manual control of the robot, accessible through any browser using the robot's IP address. It communicates with ROS 2 via a WebSocket server, with each interface element subscribed to its corresponding ROS 2 topic. The interface provides teleoperation controls, fork raise and lower buttons, and an emergency stop function.

Sensor data including LiDAR and ultrasonic obstacle distances, battery voltage, current level, and three limit switch statuses are displayed in real time, with each switch indicator turning green upon activation. A live camera feed is also available for visual monitoring of the pallet detection and docking process.

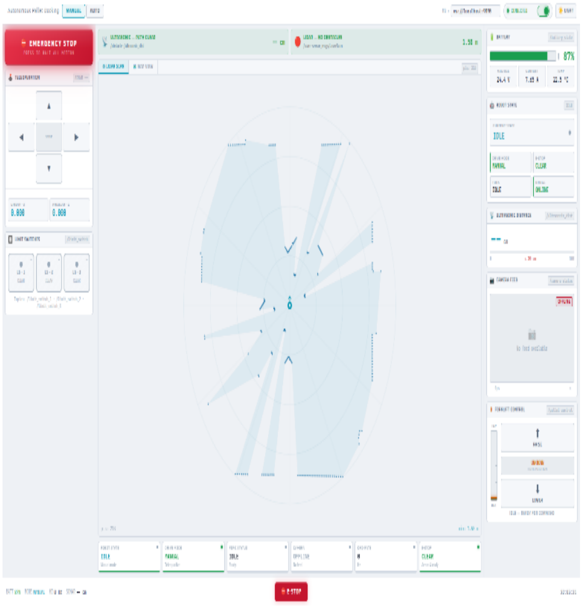

Figure 4 **Web based GUI control**

3. Methodology

3.1.Map Generation And Location Setup

Before the robot begins operation, the indoor workspace is scanned using the onboard LiDAR while the robot is guided manually. The scan data is processed through a SLAM algorithm to produce a two-dimensional occupancy map, which is stored for repeated use. Three target locations are then marked on this map — the initial standby point, the pallet pickup area, and the drop-off destination — which the robot references throughout every task cycle[18].

3.2.Pose Estimation and Autonomous Traversal

When a task begins, the robot compares real-time LiDAR readings with the stored map to determine its current position through AMCL. Rotational data from both drive wheel encoders is merged and cleaned using an EKF, producing a consistent odometry stream that strengthens localization accuracy. Nav2 receives this pose information and generates a safe travel route using the NavFn planner, while the DWB controller manages velocity adjustments to keep the robot on track during movement[19].

3.3.Visual Detection and Docking Alignment

Upon arriving near the pallet area, the camera is enabled to search for April Tags attached to the pallet frame. The spatial coordinates of each identified tag are averaged to obtain a centroid, indicating the pallet's center point[20]. Using this reference, the robot makes small corrective movements in both angle and position until the centroid is centered along its approach axis, preparing it for accurate fork entry.

Figure 5 Pre-Engagement Position Of The Robot With Pallet

3.4.Insertion, Clamping and Lift Execution

The robot inches forward until the fork slides fully under the pallet. The first limit switch, triggered by frame contact, signals that insertion is complete. The lead screw then drives the scissor arms upward, raising the pallet steadily. When the second limit switch fires at the upper mechanical boundary, the lift is stopped and the pallet is considered secured. Control of obstacle detection passes to the ultrasonic sensor as the robot begins moving toward the drop-off point.

Figure 6 Fully Inserted And Lift-Ready Position

3.5.Controlled Lowering and Cycle Reset

At the drop-off location, the lead screw direction is reversed, bringing the scissor arms down and settling the pallet onto the floor. The third limit switch confirms ground contact, after which the robot withdraws the fork and navigates back to the standby position, resetting for the next cycle.

3.6.Performance Measurement

Each trial is assessed using navigation positional error, tag-based alignment offset, total cycle duration, and obstacle detection latency as key metrics. Multiple simulation runs are conducted to verify consistency. The web interface serves as a live observation tool during evaluation, displaying sensor states and confirming smooth transitions across all operational phases.

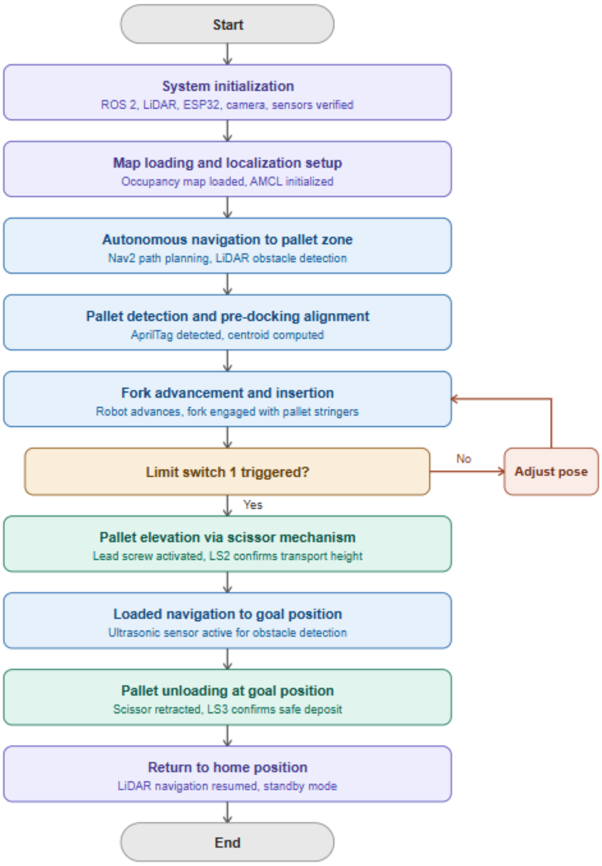

Figure 7 **Operational Workflow**

4. Results And Discussion

4.1.Results

The system was tested in a Gazebo-based warehouse simulation using ROS 2 Humble. The robot successfully navigated between all predefined positions using AMCL localization and Nav2 path planning. April Tag detection accurately computed the pallet centroid for alignment, and limit switch feedback confirmed proper docking before lifting. The scissor lift performed stable pallet handling, and the ultrasonic sensor ensured safe obstacle avoidance during loaded transport. The complete workflow was executed consistently across all test runs.

4.2.Discussion

The results confirm that combining LiDAR navigation, vision-based alignment, and closed-loop feedback within a single ROS 2 framework produces a reliable and repeatable pallet handling system. The metal-stamped AprilTags and two-stringer pallet design reduced docking errors, while the three-stage limit switch sequence eliminated open-loop dependency. The system proves to be a cost-effective and scalable approach for small-scale warehouse automation.

Conclusion

This paper presented an autonomous pallet docking system integrating LiDAR navigation, AprilTag vision, scissor lift mechanics, and a web-based monitoring interface within ROS 2. The system successfully completed the full handling workflow in simulation. Future work will focus on real-world deployment, improved perception under varying conditions, and increased payload capacity for industrial applications.

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