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Automated Power Management: Designing an Autonomous Mobile Robot Docking System for Seamless Charging

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Abstract

This paper presents the design and implementation of an autonomous docking system that allows a mobile robot to recharge without human intervention. With mobile robots increasingly deployed in industrial and service settings, autonomous power management is needed to keep them running with minimal downtime. The system uses computer vision with ArUco markers: markers placed on the charging station are detected by a webcam mounted on the robot, and their position and orientation are used to compute the robot's displacement and its distance from the target. The robot then moves forward or rotates until it is aligned closely enough for docking. Electrical contact is made through pogo pins, spring-loaded connectors on the robot's front face that meet matching contacts on the fixed structure. Pogo pins were chosen because they tolerate repeated insertion, absorb the small misalignment that vision-based docking leaves behind, and allow relays to be opened safely once contact is established, which limits sparking. The design includes sensors for environmental perception, algorithms for localization and navigation, and a power management system with fail-safe mechanisms against overcharging and overheating. The architecture is modular, so it can be adapted to different charging infrastructure and different robot models.

Index Terms— *ArUco markers, autonomous mobile robot, autonomous docking, computer vision, docking station, pogo pins, power management, robot charging.*

I. Introduction

Automated power management is an active area in robotics. As demand for autonomous systems grows across industries, efficient charging solutions matter more. A docking system for an autonomous mobile robot removes the need for manual intervention in charging, which improves operational efficiency and reduces downtime.

The key components of such a system are sensors, navigation algorithms and a docking mechanism. These work together to align the robot with the charging station and establish a connection without a human present. The design also includes power management features intended to optimize energy consumption and extend battery life. The system is meant to be adaptable across environments. Whether deployed in a manufacturing facility, a warehouse or service setting, it offers a solution that can be customized to specific requirements. This paper describes the design principles, the technological components and the operational benefits of the system.

II. Literature Survey

An autonomous mobile robot should be able to work automatically throughout its operation, handling scheduled tasks, power recharging, localization and path planning. Docking is one of the processes that makes fully automatic operation possible.

Several studies have investigated docking by combining LiDAR with various sensors, markers and mechanisms to find the position and orientation of the robot relative to the station. One approach proposes an automatic docking system for recharging a surveillance robot, based on self-localization of the robot together with infrared detectors at the docking station; both the robot and the station were designed around an arc-shaped docking interface. Another combines ArUco codes with infrared distance sensors, using the ArUco code as a landmark so the robot can perceive its position relative to the dock. Experiments from different starting points demonstrated the robustness of that solution, and it is the approach the present work builds on. A third uses a portable effector docking mechanism for path planning and localization, developing the docking process from LiDAR readings and a precision marker on the station, which avoids modifying the hospital floor on which the robot operates.

Work on vision- and LiDAR-based docking for machine tending in manufacturing addresses the difficulty of detecting charging stations in unstructured environments. That research combines deep learning, using YOLOv7-based object detection, with LiDAR sensors for recognition and docking, aiming to improve recognition accuracy while reducing computation cost.

Research on reference cage architecture for automotive production systems addresses the need for high-accuracy docking in material handling. Traditional navigation methods often rely on physical restraints at the docking station, which limits flexibility. The reference cage architecture uses multiple reference points to maintain scan-matching-based localization throughout docking, achieving sub-centimetre accuracy with a real-time reference selection mechanism, validated in an automotive production plant.

III. Proposed System

The proposed solution is a complete system for autonomous charging of a mobile robot's batteries. The two aspects to consider are the docking procedure and the charging procedure. For charging, the electrical circuits needed to supply power are integrated into a solid structure. That structure also supports the robot during docking and carries two active markers that help the robot find its way to the station. Localization is possible through the vision system mounted on the robot, consisting of a webcam and an image grabber installed on the robot's onboard computer. The complete arrangement is shown in Fig. 1.

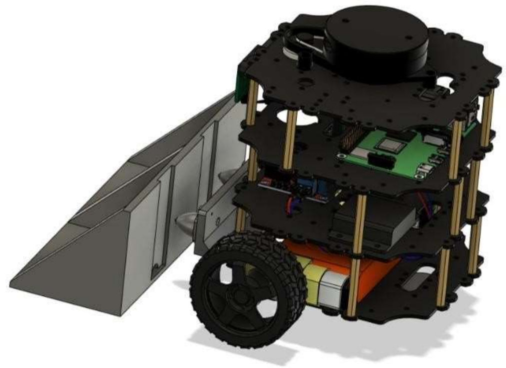

Fig. 1. Docking station with servo motor, AMR and marker.

The markers on the docking station act like range lights. When low battery power is detected, the robot stops its current task and moves into the vicinity of the docking station. Using the webcam, it takes the information given by the marker positions to calculate its displacement and evaluate its distance to the target. It then moves forward or rotates to ensure a safe approach. Once it enters the station, the contacts on the robot's front side fit into the matching electrical contacts on the fixed structure.

IV. Docking Station

A. Function and Infrastructure

The docking station is the hub for charging and maintenance. It provides a defined location for the robot to navigate to and dock at when power is low. Docking stations are placed strategically within the operational environment to optimize robot navigation and minimize downtime. By standardizing the charging process and providing a central point for maintenance, they streamline operations and extend the working life of the robot. They also support scalability, since a station can accommodate multiple robots in sequence.

A docking station consists of an electro-mechanical station and its software. The software instructs the robot on how to reach the station, and the docking algorithm is based on a low-cost alignment method. The station and robot together provide a mechanical and electrical connection between the charging system and the robot. Algorithms monitor the battery voltage, control the docking procedure and account for errors.

B. Docking Interface

The docking interface combines sensors, communication protocols and mechanical mechanisms. Sensors on the station and the robot detect each other's presence; these may be infrared sensors, ultrasonic sensors or cameras. The station and robot communicate using established protocols, so that the robot can receive instructions and report its status, including battery level and any errors during docking.

Once the robot has located the station, it aligns itself so the charging connectors match the ports on the station, then moves closer until contact is made. The station may include mechanisms to secure the robot during charging, such as locking pins or magnets. Throughout charging, both sides monitor status, so that a poor connection or a malfunction can be detected and acted on, whether by repositioning the robot or alerting maintenance personnel.

C. Navigation and Localization

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The robot determines its position within the environment using a combination of cameras, LiDAR, ultrasonic sensors, wheel encoders and inertial measurement units. Processing this data with SLAM algorithms lets the robot build a map of its surroundings and locate itself within that map. Path planning then produces a route to the destination, taking into account the robot's current position, the location of obstacles, its own size and shape, and any constraints on its movement. The control system uses the planned path to adjust velocity and steering.

When the robot reaches the docking station, it uses the same localization and mapping capability to manoeuvre into position, aligning with the markers on the station and adjusting position and orientation until it is correctly placed.

D. Power Management

The docking station is connected to a power source, which charges the robot's batteries. When the robot docks, the power management system detects this and starts charging, monitoring battery level and adjusting the charging rate so that the batteries are not overcharged. Safety features prevent overheating and other hazardous conditions; temperature sensors monitor the batteries and cut off charging if safe limits are exceeded. Energy-efficient charging techniques such as trickle charging are used to extend battery life.

V. Pogo Pins

Pogo pins, also called spring-loaded pins, are small connectors that establish an electrical connection between two devices. They are durable and withstand mechanical shock and vibration, which is why they are used in electronics testing and in docking applications. A complete connection path requires a mating receptacle for the pin to engage, called a target or land: a flat or concave metal surface which, unlike the pin, has no moving parts. On a printed circuit board the target may simply be a plated area. Spring-loaded pins are precision parts made by turning and spinning rather than moulding, which allows small production quantities at lower cost.

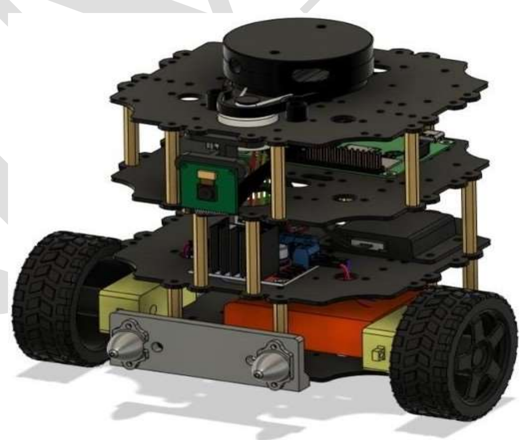

Fig. 2. Pogo pins mounted on the robot, with webcam and servo motor.

A. Structure

A pogo pin consists of four main parts: a spring, a pin head, a barrel or body, and a plunger. The spring gives the pin its compression and expansion, and is usually made of stainless steel or beryllium copper for resilience under repeated compression. The pin head at the top makes contact with the mating surface and is often gold-plated for conductivity and corrosion resistance. The barrel houses the spring and provides structural support, typically cylindrical and made of brass or stainless steel. The plunger retracts the pin head into the body when not in use, which protects it from damage and contamination.

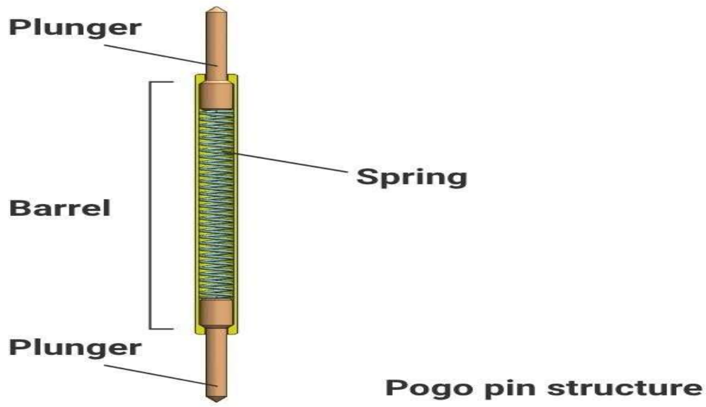

Fig. 3. Basic internal structure of a pogo pin.

B. Working

When force is applied to the pin, the spring compresses and the plunger moves into the barrel. The shape of the barrel retains the plunger, stopping the spring from pushing it out when the pin is not locked in place.

In electrical contact design a certain amount of friction is needed to hold a connector in place and retain the contact finish, but high friction increases stress and wear on the contact springs and housings. A precise normal force, typically around 1 newton, is required to generate the necessary friction. Because a spring-loaded pin needs a slight gap between plunger and barrel so that it can slide, momentary disconnection can occur under vibration or movement. To counter this the plunger is usually given a small tilt, which keeps the connection continuous.

Pogo pins also minimize the risk of sparks and voltage peaks. Once contact is established, the pins allow relays inside the robot and inside the docking station to be opened safely.

C. Integration and Types

Integrating pogo pins onto a robot requires mounting points or receptacles positioned for easy alignment with the charging station, pins selected for the current rating, contact resistance and environmental conditions of the application, secure mechanical mounting, properly insulated wiring with attention to polarity, and testing and calibration of alignment and contact pressure before deployment. The pins should be inspected regularly for wear and cleaned to prevent debris buildup.

Several types are available. Spring-loaded pogo pins are the most common in docking systems. Single-pin connectors use one pin against a corresponding pad and are simple but reliable. Multi-pin connectors arrange several pins in a fixed configuration, allowing power, data and signals to be transmitted at the same time. Gold-plated pins offer better conductivity and corrosion resistance for high-reliability applications. Customized pins can be developed where a specific design or additional function is required.

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VI. Aruco Markers

ArUco markers are two-dimensional barcodes designed for computer vision, used in augmented reality, robotics and camera calibration. They are square fiducials made of a grid of black squares on a white background, with a unique pattern encoded in the grid that identifies each marker and determines its orientation. The name stands for Augmented Reality University of Cordoba, where they were developed. ArUco is an open-source library for detecting squared fiducial markers in images, and where the camera is calibrated, the pose of the camera relative to the marker can be estimated.

ArUco markers carry fewer embedded bits than a QR code, which makes them computationally easier to identify. This is the property that matters for docking, where detection must run continuously on the robot's onboard computer while it is also navigating. Marker sizes range from 4 × 4 to 7 × 7, with 50, 100, 250 and 1000 available IDs.

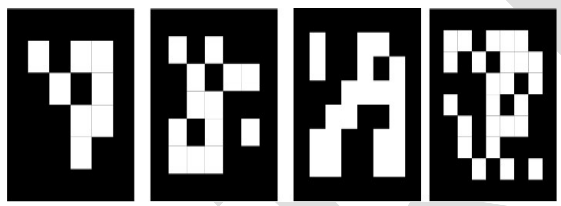

Fig. 4. ArUco markers with different matrix sizes (4 × 4, 5 × 5, 6 × 6 and 7 × 7).

Multiple markers can be detected at once. For example, four ArUco markers placed at the corners of the space in which the robot operates allow the code to detect all four and calculate the homography matrix. The homography corrects the perspective transformation and gives the real-world coordinate of any point within the defined space, including the position of the robot itself.

A. Key Features

Unique identification. Each marker carries an identification number encoded in its internal binary grid, so several markers can be distinguished within one image.

High contrast. The black-and-white square design gives strong contrast, which makes detection reliable under varying lighting.

Rotation and scale invariance. The internal grid determines the marker's orientation, so it is detected correctly regardless of how it is rotated or how far away it is.

Open-source library. Detection is supported by an open-source library, which reduces the implementation effort and makes the approach accessible.

B. AR Tags

AR tags are visual markers used to trigger augmented reality content, and come in various forms including simple black-and-white patterns. They serve a similar purpose to ArUco markers in giving a camera a known reference in the scene. The difference is one of intent and structure: ArUco markers are designed specifically for pose estimation and carry a compact binary payload optimized for fast, robust detection, whereas AR tags are a broader category oriented towards content triggering. For docking, where what is needed is an accurate pose estimate computed many times per second, the ArUco design is the better fit.

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Fig. 5. Augmented reality (AR) tags.

VII. Applications

Autonomous mobile robots that manage their own charging can operate continuously across a range of settings. Three are described here.

A. Cleaning and Maintenance

Robots fitted with brushes, vacuums, mops or sprayers perform cleaning tasks indoors, navigating floors and other surfaces autonomously. They follow predefined cleaning routes or adapt their paths from real-time sensor data. Robots equipped with cameras and sensors also carry out routine maintenance inspections, navigating through buildings or industrial sites to inspect structural elements, machinery and utilities for wear, damage or malfunction, capturing images for analysis and generating reports.

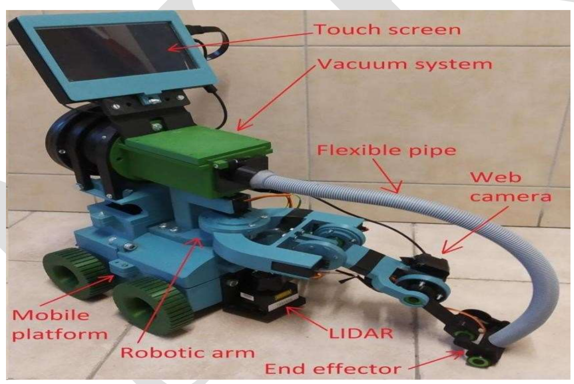

Fig. 6. AMR vacuum cleaner.

B. Security and Surveillance

A surveillance robot uses LiDAR, cameras and depth sensors to build a map of its environment and navigate autonomously while avoiding obstacles and following patrol routes. Security personnel program patrol routes and points of interest covering entrances, corridors and sensitive zones. Sensors detect motion, heat, sound and gas levels, and computer vision recognizes objects and people in the field of view, so that unusual activity triggers an alert. Cameras stream live video to a control station, allowing personnel to assess a situation and respond. The robot logs timestamps, sensor readings and video for later analysis. When not patrolling it returns to its charging station automatically, which is what makes continuous coverage possible.

The same platform can assist with HVAC maintenance, inspecting ductwork, filters and other components, and reaching areas within ducts and air handling units that are difficult to access. Early detection of problems through automated inspection helps prevent system failures and maintain indoor air quality.

Fig. 7. HVAC system.

C. Hospitality

In hotels and resorts, mobile robots navigate autonomously to deliver services. They greet guests on arrival, assist with check-in and give information about amenities and local attractions. They deliver room service items such as towels, toiletries and refreshments, navigating corridors and lifts without assistance. Acting as virtual concierges, they recommend restaurants and attractions and help with reservations. They support housekeeping by delivering fresh linen and supplies and collecting used items, and they assist guests with luggage between the lobby and their rooms.

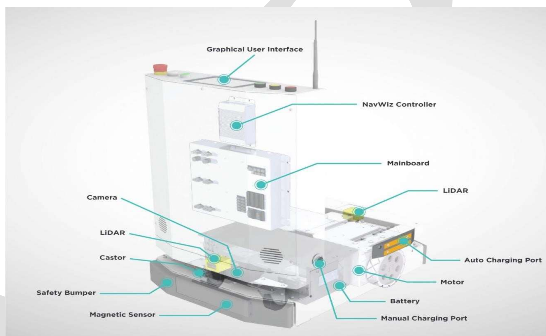

Fig. 8. Hospitality AMR.

VIII. Results And Discussion

The docking system integrates charging into the robot's workflow so that operation continues without manual intervention. The design and implementation are based on standard electronic components integrated into a power management system board, which includes a limit switch, an infrared sensor and an integrated circuit. A prototype board was mounted on a four-wheeled robot with three applicative levels, each with its own industrial PC handling specific tasks. Communication between the industrial PCs takes place over RS232 and RJ45 ports, and the robot communicates with the battery charger using infrared.

On efficiency, the aim is to reduce the number of recharging operations during working hours. The robot can work continuously for at least 14 hours per day depending on battery capacity. The system achieves a recharging time of approximately 7 hours for a 24 V battery discharged from 18 V.

On reliability and safety, the system recharges without causing electrical damage to either the robot or the charger during docking, and can safely recharge the battery of any autonomous robot correctly connected to the charger. The combination of vision-based approach and spring-loaded contacts is what delivers this: vision gets the robot close enough, and the compliance of the pogo pins absorbs the residual misalignment that vision alone leaves.

IX. Conclusion

An autonomous docking system for seamless charging advances power management for mobile robots. Enabling a robot to navigate to a charging station and dock without assistance extends its working autonomy and improves operational efficiency. This addresses the requirement for continuous operation in industrial, warehouse and service environments, and reduces downtime by removing manual intervention from the charging cycle.

Combining computer vision for approach with pogo pins for connection keeps the system inexpensive relative to solutions built around precision mechanical guides or high-end sensors, while remaining tolerant of the alignment error that a vision-based approach inevitably leaves. The modular architecture means the same design can be adapted to different charging infrastructure and different robot models.

X. Future Scope

Efficiency improvement. Optimizing charging schedules, monitoring battery health and adjusting charging parameters from real-time data would further reduce downtime.

Scalability. As autonomous robots spread across manufacturing, logistics, healthcare and agriculture, the docking system needs to scale to fleets rather than individual robots.

Integration with IoT and AI. IoT sensors can supply real-time data on power consumption, battery status and environmental conditions, and AI algorithms can use that data to optimize charging strategy and predict maintenance needs.

Adaptability. The system should dock reliably in indoor factories, outdoor warehouses and dynamic environments with obstacles.

Safety and reliability. Fail-safe mechanisms against overcharging and overheating remain essential as charging currents rise.

Cost-effectiveness. The upfront cost of an automated power management system is offset over time by increased productivity, reduced downtime and longer equipment life.

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