Semi-Autonomous Locomotion Using Rotary Encoders

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Abstract*—This paper presents the design, development, and evaluation of an autonomous Locomotion robot intended for versatile and efficient mobility in various environments. Unlike conventional robots, our bot employs a unique wheel configuration allowing it to move seamlessly in any direction without the need for reorientation. The mechanical design features omni wheels, enabling precise control over movement. The electrical system integrates multiple sensors and an advanced microcontroller to enhance responsiveness and accuracy. Our software architecture incorporates real-time kinematic algorithms, providing robust navigation and obstacle avoidance capabilities. Comprehensive testing in diverse scenarios demonstrated the robot's superior agility, stability, and operational efficiency. The results highlight significant improvements over traditional wheeled robots, particularly in constrained and dynamic spaces. This research contributes to the field by offering a scalable solution for applications ranging from industrial automation to search and rescue missions. Future work will focus on optimizing control algorithms and expanding the robot's autonomy.

I. INTRODUCTION

Autonomous locomotion robots are a giant step in robotics, superior in mobility. Traditionaly wheeled robots can't move sideways without turning their orientation, which makes them less efficient in tight spaces. On the other hand, with omnidirectional robots equipped with three omni wheels, they easily make movement in all directions, handy for agile functionality in such tasks as industrial automation and operations involving search and rescue

Localization is very important to navigate accordingly. The method implemented is an odometry application, which utilizes an IMU sensor and rotary encoders for the achievement of more accurate positions [1]. The control system used in the optimization of motor acceleration comprises PID control for accuracy under dynamic conditions [1].

The current generation of autonomous ground robots can perform surveillance, transportation, and rescue missions. Their locomotion is achieved through various methods, which include wheels, legs, and tracks. Each locomotion method has an advantage and a disadvantage: wheels work well on plain surfaces but are generally unsound on rough ones, while legs manage to navigate difficult terrains but are quite complex. Tracks do well on soft surfaces, but in terms of speed, it heavily restricts them [2].

The usage of 3 omni wheels acquired 360° turning is achieved by individually actuating each wheel to have agility with reduced design complexity. Robotics technology keeps advancing rapidly; hence, locomotion, navigation, and obstacles avoidance become even more critical studies [3]. &Our research is focused to enhance robot stability, control, and motion in unstructured terrains through strategies such as motion planning and active compliance control [4].

II. LITERATURE SURVEY

Mobile robotics has seen widespread application across various sectors, including exploration, security, healthcare, and education. The design of these robots is often according to its environment in which they operate and their requirement. Advancement in the technologies such as LiDAR and vision-based algorithms have contributed significantly to improving navigation and mapping capabilities [5], [6].

Several studies have explored kinematic and dynamic models of wheeled mobile robots, underscoring the critical role of independent steering and driving mechanisms in enhancing mobility. Building on these foundations, the development of Omni-directional robots, such as the OK-1, aims to provide enhanced functionalities. Despite their advantages in complex mobility, Omni robots have received less attention compared to differential mobile robots. Artificial intelligence techniques, including artificial neural networks (ANN) and fuzzy logic, have been applied to path planning and control for mobile robots. Optimization methods like particle swarm optimization (PSO) has focused on improving the PID controller performance in dynamic environments. Studies on four-wheel drive (4WD) Omni-directional robots have proven advances in motion control and efficiency, with comparisons to existing systems showing superior outcomes in terms of accuracy and performance. [7], [8], [9].

laser-based measurement instruments and gyroscope signal processing have focused on achieving higher-resolution measurements and improved noise immunity in rotary encoders, particularly in industrial applications where precision is paramount [10]. Mobile manipulation robots are being developed for search and rescue (SAR) operations. These robots were able to move across different types of terrain and handle objects. The DARPA Robotics Challenge has helped improve these robots, especially in tasks that require handling multiple objects. Path planning, which involves making robots follow straight lines and curves, is important to help them avoid collisions [11], [12].

Rotary encoders are critical components in various automation systems, precision machinery & Optical encoders, known for their high accuracy. This are often used in demanding applications, while magnetic encoders are a more cost-effective solution for less demanding requirements. Selecting the appropriate encoder depends on several factors, including design characteristics and environmental conditions. Despite their widespread use, rotary encoders face challenges related to performance degradation over time. Although accelerated degradation testing has been explored in prior research, a significant gap remains in comprehensive reliability modelling and lifespan prediction, underscoring the need for further investigation [13], [14]

Localization and tracking technology have also advanced significantly in medical robots, particularly with the creation of precise angular sensors. Prior studies have explored the use of optical and inductive encoders in minimally invasive surgeries. The ASTRAS360 project addresses the gap in high-resolution, miniaturized sensors for flexible robots, which could significantly improve the accuracy and precision of surgical procedures.

III. METHODOLOGY

The mechanical design of our robot revolves around the use of omni wheels, which are crucial for achieving holonomic movement. Each of the 3 omni wheels is mounted at the corners of the robot's chassis, enabling movement in any direction. The chassis is designed to be robust yet lightweight, providing a sturdy platform for the components while ensuring the robot remains agile. The omni wheels feature rollers placed at an angle of 30 degrees, allowing for the unique movement capabilities of the robot.

A. System Level Block Diagram of Semi-Autonomus Locomotion using Rotary Encoder

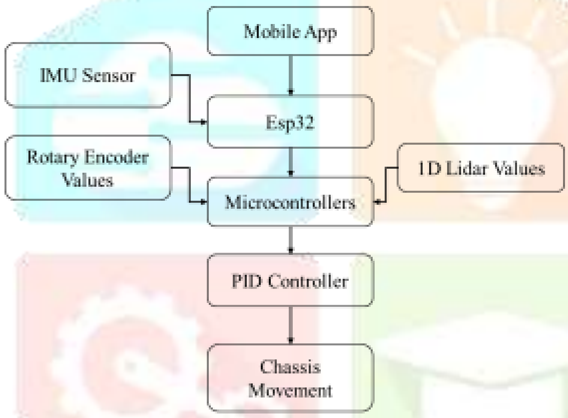

Fig. 1. System Architecture

The fig 1 shows the system architecture of the system. The electrical system integrates several key components to manage power distribution, motor control, and sensor feedback. The primary components include the Cytron motor driver, Arduino Mega, ESP32 module, rotary encoders, TFmini 1D Lidar, and a lithium polymer battery. The Citron motor driver controls the power and speed of the motors attached to the omni wheels, ensuring precise movement. The Arduino Mega serves as the main controller, handling inputs from the sensors and executing control algorithms and the vector resolutions. The ESP32 module is used for wireless communication with the mobile app, enabling remote control and monitoring. Rotary encoders are attached in X-Y direction to provide real-time feedback on wheel rotation, essential for accurate movement control. The lithium polymer battery supplies the necessary power to all components, chosen for its high energy density and lightweight properties.

B. Kinematics of 3 wheeled omni drive

Omni-directional mobile robots have been extensively researched and developed across various domains. Holonomic wheeled platforms exhibit full omnidirectional movement, allowing for simultaneous and independent control of both translational and rotational motion. To effectively control these robots, it is essential to determine the angular positions and velocities of the wheel shafts. This section presents the kinematic model of the robot.

Fig.2. Kinematic Design of 3-wheeled omni drive

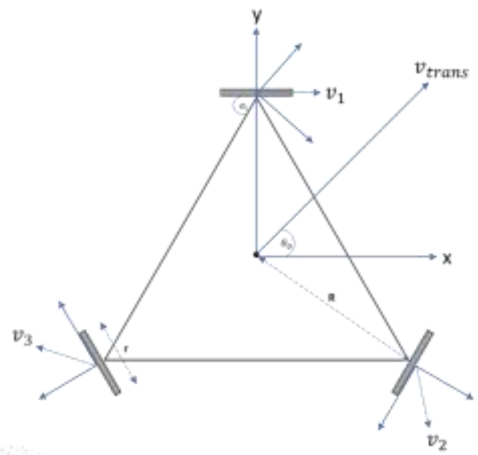

Fig.2. demonstrate the kinematic design of the 3 wheeled omni drive

The development and control of a three-wheeled omnidirectional mobile robot, offering significant advantages over conventional two-wheeled, non-holonomic robots. The methodology includes developing a kinematic model using both local and global reference frames, where each wheel is positioned at an angle relative to the local frame, and its contribution to movement is determined by its angular velocity. The translational velocity of the robot is calculated based on the robot's global velocity and platform rotation speed. The relationship between translational and angular velocities is mapped using vector equations, forming the basis of the kinematic model that enables omnidirectional movement. The inverse Jacobian matrix is used to derive the wheels' angular velocities from global velocity, providing precise control of the robot's movements and facilitating the transformation between global and local coordinates. A simulation is conducted to verify the kinematic model, where the robot's trajectory from an initial pose to a desired pose is simulated with error minimization strategies in place to reduce trajectory error. Various configurations are tested, and the error is minimized using the Jacobian matrix, with the trajectory error decreasing exponentially. The simulation graphically demonstrates the effectiveness of the control system in maintaining accurate trajectories and minimizing errors.

The PID controller is employed to regulate the robot's speed and position by adjusting the control inputs based on the error between the desired and actual trajectories. The Proportional (P) component provides a correction proportional to the current error, the Integral (I) component accounts for the accumulation of past errors to eliminate steady-state errors, and the Derivative (D) component anticipates future errors by considering the rate of error change. By tuning the gains for each component (P, I, D), the PID controller ensures stable and accurate control over the robot's movement. The algorithm calculates the control signals by continually updating the error and applying the

PID formula to minimize the deviation from the desired path. A feedback loop is established to monitor the robot's position and velocity, allowing the controller to continuously adjust the wheel speeds to follow the desired trajectory. The simulation demonstrates that the PID-controlled system successfully minimizes errors in both position and orientation, ensuring smooth and accurate motion even under dynamic conditions.

In this system, a mobile app serves as the controller for the three-wheeled omnidirectional robot, allowing the user to input a target destination. Once the destination is provided, the system calculates the number of wheel rotations required for the robot to reach that point using basic trigonometry and geometry. This calculation involves determining the angle at which the robot's chassis should be moving, considering the relationship between the robot's current and desired positions.

The system is equipped with encoders mounted on the robot in the x and y directions, oriented 90 degrees relative to each other. These encoders provide real-time feedback on the robot's current position, allowing the system to continuously monitor its coordinates. By comparing the current position with the destination coordinates, the system computes the angle at which the robot must move to align with the target. This real-time positional feedback enables the robot to dynamically adjust its trajectory during movement. Additionally, 1D LiDAR sensors are mounted in four directions around the robot to continuously scan for obstacles in its path. These sensors help the system detect any sudden obstacles that may appear, enabling the robot to take immediate evasive action. The LiDAR data also assists in precise localization by providing accurate environmental mapping.

To further enhance the robot's precision in movement and localization, a PID control algorithm is implemented. The PID controller fine-tunes the robot's motion by adjusting wheel speeds based on feedback from the encoders and LiDAR. The Proportional (P) component of the PID controller corrects errors between the current and target positions, the Integral (I) component eliminates accumulated errors over time, and the Derivative (D) component prevents overshooting by anticipating future errors. This combination of PID control and real-time data from the encoders and LiDAR ensures smooth, accurate navigation, even in complex environments with obstacles.

C. Algorithms

a. Algorithm for kinematics of 3wheeled omni drive and PID control

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Algorithm 1: Kinematics of 3 wheeled omniDrive

Input :

Desired position: $P_{des} = (x_{des}, y_{des}, \theta_{des})$

Time step t_s

Wheel radius r

Distance from the robot centre to wheels R

Output :

Steps:

1. **start**
2. Compute translation and rotational velocities for each wheel:

$$v_i = v_{trans} + v_{rot}$$

Where:

$$v_{trans} = -\sin(\theta + \alpha_i) \cdot x + \cos(\theta + \alpha_i) \cdot y$$

$$v_{rot} = R \cdot \theta$$

3. Relate wheel velocities to the angular velocities:

$$v_i = r \cdot \dot{\theta}_i$$

4. Define the inverse Jacobian matrix to map global velocities to wheel angular velocities:

$$\dot{\theta} = J^{-1} \cdot u$$

5. At each time step, compute the robot's position and compare it with the desired position:

$$E = \| P_0 - P_{des} \|$$

6. Update the robot's position using the differential kinematics equations:

$$P_k = P_{k-1} + t_s \cdot P_k$$

7. Update the robot's position using the differential kinematics equations:

$$\frac{dE}{dt} = \frac{dP_0}{dt} - \frac{dP_{des}}{dt}$$

8. Apply corrections to reduce the error

$$\dot{\theta} = J^{-1} \cdot \lambda E$$

Variables used in Algorithm 1:

- $x_{0,}y_0$: Initial X and Y coordinates
- x_{des}, y_{des}: destination X and Y coordinates
- $x_{0,}y_0$: Initial X and Y coordinates
- θ_0: Initial orientation of robot
- θ_{des}: *Desired orientation of the robot*
- $t_{s,}$: time step for control loop
- r: radius of wheels
- R: Distance of the wheels from the centre of the robot to the centre of the wheels
- v_i: Total velocity of each wheel
- v_{trans}: Translational velocity component of the robot in global frame
- v_{rot}: Rotational velocity component of the robot in the global frame
- θ : orientation of the robot in the global frame
- α_i: Angle at which each wheel i is positioned with respect to local frame
- $\dot{\theta}_i$: Angular velocity of wheel i.
- J: jacobian matrix
- E: Trajectory error, defined as the difference between the current position and the desired position .
- λ : A control gain parameter used in error minimization to adjust how quickly the robot corrects its trajectory.
- P_k: Position of the robot at time step.
- $\dot{P}$: Change in position with respect to time, representing velocity in the task space

The kinematic model and PID control algorithm ensure smooth trajectory tracking and error minimization, while the integration of wireless communication enables easy remote operation. The system's robust architecture, combined with advanced control strategies, demonstrates the effectiveness of the robot in dynamic, real-world scenarios. Future improvements may focus on enhancing the obstacle avoidance capabilities, refining the control algorithms for even greater precision, and incorporating additional sensors for more complex tasks such as SLAM (Simultaneous Localization and Mapping). Overall, this system represents a significant step toward versatile and intelligent robotic platforms capable of autonomous navigation and interaction with their surroundings.

IV. RESULT AND DISCUSSION

The omnidirectional robot developed in this study demonstrated exceptional precision and agility across various test scenarios, including straight-line, diagonal, and rotational movements. These maneuvers were executed with minimal deviation, thanks to real-time feedback from rotary encoders and 1D LiDAR sensors. The integration of omni wheels, combined with the finely tuned control algorithms, was critical in achieving this level of performance.

Fig 3. Shows the real life prototype of the system.

Distance (cm)	proportional component	Error (cm)
100 cm	*0.68*	±2
500 cm	*1.19*	±7
750 cm	*1.26*	±9
1000 cm	*1.73*	±10
1500 cm	*1.89*	±19

Fig. 4. Shows Analysis of the error values with respect to distance and proportional component

Fig. 3 shows the real-life prototype of the system, and **Fig. 4** illustrates the error values analyzed with respect to distance travelled from the current position and destination, along with the proportional component (P) of the PID controller. The system's power consumption was kept within acceptable limits, with a lithium polymer battery providing sufficient energy for extended operations. The energy efficiency was further enhanced by the low-friction omni wheels and optimized control algorithms.

The robot maintained stability even during high-speed movement, underscoring the robustness of its mechanical design and control system. Its quick response to control commands makes it highly suitable for dynamic environments. Performance metrics revealed significant improvements in movement, speed, and stability compared to conventional wheeled robots. These results validate the proposed design and methodology, demonstrating the potential for omnidirectional robots in practical applications such as warehouse automation, surveillance, and service robotics. This study paves the way for future enhancements in sensor integration and control strategies, further expanding the robot's capabilities.

V. CONCLUSION

The development and evaluation of the omnidirectional robot have yielded promising results, demonstrating its potential to revolutionize robotic mobility in diverse applications. By leveraging advanced control algorithms and omni wheel technology, we have created a robot capable of precise and agile movement in any direction. The integration of components such as the Citron motor driver, Arduino Mega, ESP32 module, 1D Lidar, and rotary encoders has enabled seamless coordination and control, resulting in fast response times and stable performance.

Our research has validated the effectiveness of the design and implementation methodology, showcasing the advantages of omnidirectional mobility in various scenarios. The robot's ability to navigate through constrained spaces, execute complex manoeuvres, and maintain stability under dynamic conditions underscores its suitability for applications such as industrial automation, surveillance, and search and rescue operations.

Looking ahead, there are several avenues for future research and development to further enhance the capabilities of omnidirectional robots. Refinements in control algorithms, sensor integration, and mechanical design could improve efficiency, autonomy, and versatility. Additionally, exploring new materials and manufacturing techniques may lead to lighter and more durable robot designs, further expanding their potential applications.

In conclusion, the omnidirectional robot represents a significant step forward in robotic mobility, offering unparalleled agility and manoeuvrability. This research sets a foundation for continued innovation in the field, with the potential to unlock new possibilities in robotics and automation. As we continue to refine and optimize our designs, omnidirectional robots will play an increasingly vital role in addressing complex challenges and advancing technology for the benefit of society.

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