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The Autonomous Movement of an Omnidirectional Robot along a Calculated Trajectory

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Abstract. This work focuses on the difficulty of autonomously moving wheeled robots over very rough terrain where traditional navigation techniques fail. The ultimate goal of the research work is to create dynamic and mathematical models that can make the robot maneuver through complex surfaces and also avoid obstacles. Performance was tested using simulations and real-world practice in conditions such as uneven surfaces and even challenging obstacles. Key findings are that the proposed models improve the trajectory accuracy and traversal time and make the robot more robust to environmental changes. The implementation of sensor fusion technologies also enhanced the robot's environmental understanding, allowing for more effective obstacle avoidance. These models can be used in practice for applications such as search and rescue, environmental exploration, and autonomous monitoring. The study brings to our attention the models considered to leverage such applications. Our methodology consists in constructing an advanced dynamic model to reproduce wheel-terrain interactions, along with control algorithms that can react against variations in real-time terrain. The experimental design consists in testing the robot on different types of surfaces, such as rocky, sandy, and irregular terrains. The effectiveness of the proposed solutions was evaluated using metrics like trajectory accuracy, obstacle avoidance success rate, and traversal time. Integration of dynamic and mathematical model improved the obstacle avoidance ability as well as the overall navigation performance. It opens an avenue for future research, where more advanced control strategies may be implemented, such as machine learning algorithms, that would allow for even more adaptive and intelligent behavior to be exhibited from a wheeled robot. Moreover, real-time terrain mapping and human-robot interaction models can be new directions to explore additional improvements of autonomous systems in different types of complex environments. By enabling robots to navigate diverse terrains with improved precision and adaptability, this research contributes to the evolution of cutting-edge technology in wheeled robot navigation towards more versatile and dependable autonomous systems in various applications, including exploration, agriculture, and disaster response.

Keywords: wheeled robots, rough terrain, obstacle avoidance, exploration, control strategies, search and rescue, dynamic models, perception of environment

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Автономное движение всенаправленного робота по рассчитанной траектории

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Аннотация. Статья посвящена исследованию автономного движения колесных роботов в условиях пересеченной местности, где традиционные методы навигации сталкиваются с трудностями. Основная цель исследования заключается в разработке динамических и математических моделей, которые позволят роботу эффективно перемещаться по сложным поверхностям, избегая препятствий. В ходе экспериментов и моделирования была оценена производительность робота в различных условиях: от неровных поверхностей до сложных препятствий. Основные выводы показывают, что предложенные модели позволяют улучшить точность траекторий и снизить время прохождения маршрута, что делает роботов более устойчивыми к изменениям окружающей среды. Будущие исследования будут сосредоточены на улучшении адаптивных алгоритмов управления и взаимодействии человека с роботом для расширения их применения в таких областях, как поисково-спасательные операции и мониторинг окружающей среды.

Ключевые слова: колесные роботы, пересеченная местность, избегание препятствий, разведка, стратегии управления, поиск и спасение, динамические модели, восприятие окружающей среды

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Introduction

Wheeled ground robots have become one of the leading solutions in modern robotics with their versatile capabilities, whether it is for exploration missions in foreign environments or critical tasks in search and rescue operations. Because of their ability to travel fast across uneven terrain and navigate complicated environments, they are a crucial instrument in fields as wide as planetary exploration, agriculture, logistics, and disaster response [Bräunl, 2008].

Over the last few years, there has been growing interest in wheeled ground robots due to innovations in sensor technology, artificial intelligence, and autonomous navigation systems. These bots have been shown to be effective at performing jobs that are dangerous, laborious, or difficult from a logistical perspective for human operators. Ferguson and his team are training robots to traverse not only other worlds but also exotic locales such as farms or disaster zones, expanding our reach and understanding of our world.

Navigating uneven terrain is one of the biggest challenges faced by wheeled ground robots. Uneven surfaces, steep slopes, rocks, and obstacles are common challenges and hazards in rough terrain. Traditional wheeled robots can fail to achieve stability, traction, and control in those situations, resulting in heavy limits on mobility and applicability. However, overcoming this obstacle is essential for utilizing the complete capabilities of wheeled robots and widening their applicability [LaValle, 2006].

In this article we address the problem of traversing rough terrain using wheeled ground robots. By means of analysis, simulation, and experimentation, we are developing solutions to allow wheeled robots to travel more efficiently, stably, and autonomously on rough terrain.

Literature Review

The study of wheeled robots navigating rough terrain has been a significant area of research, with various models and methods proposed to enhance their mobility, stability, and obstacle avoidance capabilities. This section provides an overview of previous work in this domain, highlighting key challenges and research gaps that this study aims to address.

Existing Research

Many researchers have studied the performance of wheeled ground robots in harsh terrain. In particular, researchers have investigated multiple methods to enhance the maneuverability, balance and control of such robots over difficult terrain. A few studies present improved wheel designs and suspension systems for better traction and adaptivity to rough terrains. Other researchers explored advanced control algorithms combined with sensor integration techniques to facilitate autonomous navigation within wheeled robots through intricate terrain.

Research has also focused on wheeled robots navigating different types of rough terrain, including rocky terrain, sandy desert, forest floor, and urban environments. These studies have yielded valuable insights into parameters that affect the performance of wheeled robots, including wheel-terrain interaction dynamics, terrain morphology, and environmental conditions [Ferreira et al., 2008].

1. Key Challenges

Moreover, there are still many issues that wheeled robots solve on rough terrain as the state of the art has improved significantly. The main problem is uneven surfaces, which make them unstable and compromise traction, a drawback that weighs heavily on conventional wheeled designs. Things like rocks, tree roots and debris can also slow the robot down and heighten the chances of running into obstructions or getting stuck. Furthermore, differences in the environment features (e.g., slopes, slides) cause higher difficulty in balancing and maintaining stability of wheeled robots.

And another, similar concern is traction – being able to hang onto uneven, bumpy ground enough to move over it safely and usefully. Conditions like loose gravel or mud can cause wheel slippage, resulting in performance losses as well as energy overuse. Moreover, the interaction between wheel geometry, material properties, and terrain characteristics plays an important role in traction and maneuverability [Acir, 2019].

2. Identified Gaps

Although existing research has greatly contributed to the development of wheeled robots, their limits leave several areas still requiring in-depth studies. A specific gap is that there are limited comprehensive dynamic models, capable of describing the complex dynamics between wheeled robots and rough terrain. Many of the existing models oversimplify the underlying dynamics of the terrain or ignore other significant elements, restricting their predictive power and practical applications.

Additionally, real-time adaptive control strategies are required to cope with dynamic terrains and unforeseen obstacles. Such methods have been developed using predefined maps or assumptions on the terrain features that may not be valid in unpredictable environments. Adaptive control is needed that responds autonomously to changing terrain conditions in order to improve the performance and safety of wheeled robots operating in rough terrain environments.

Finally, although some studies focus on individual aspects of wheeled robot mobility over rough terrain (for example, wheel design or terrain sensing), there has not been any sufficient research integrating these concepts into a single, cohesive framework. To address this gap, we outline a system approach by jointly considering terrain perception, motion planning and control, as their interdependencies throughout rough terrain navigation are apparent [Ali et al., 2020].

3. Problem Statement

This article focuses on enhancing the performance of wheeled ground robots when navigating rough terrain. Despite advancements in robotic technologies, wheeled robots continue to face significant challenges in operating under unstructured terrain conditions, encountering obstacles, and adapting to unstable surface conditions. The limitations of conventional wheeled designs and the complexities introduced by rough terrain hinder their mobility, stability, and overall efficiency, restricting their effectiveness in practical applications.

In this study, we propose novel solutions and approaches to address these challenges, particularly in rocky terrain. Our goal is to enable wheeled robots to navigate difficult surfaces autonomously and reliably by developing advanced dynamic models, mathematical algorithms, and control strategies. Overcoming these challenges could lead to breakthroughs in various applications, including exploration, agriculture, disaster response, and infrastructure inspection, ultimately advancing the state of robotic mobility and expanding the use of autonomous systems in challenging environments (Azeez, Muhaimeed, 2016).

4. Methodology

This study applied a holistic method to solve the obstacles faced by wheeled ground robots while traversing rugged terrain. The approach included theoretical analysis, modeling and simulation, as well as experimental validation which offered integrated solutions to enhance the robot performance under rugged environments.

4.1. Models and Theoretical Frameworks

To create theoretical concepts and models for the dynamics of wheeled robots on uneven terrain, the researchers based their work on established principles of mechanics, robotics and control theory. Dynamic models including critical terrain parameters such as wheel-terrain interaction dynamics, vehicle kinematics and terrain classification were integrated into various wheeled robot simulations in a different terrain condition including rocky surfaces, sandy terrain, and urban landscapes. Differential equations and optimization algorithms were among advanced mathematical techniques employed to define and solve equations for robot motion and control.

4.2. Wheeled Robot design and construction

An experimental wheeled robot platform was designed and built to validate/implement the proposed techniques. It featured a sturdy chassis to endure harsh terrain and to accommodate diverse sensors, actuators, and control systems for independent functionality. Wheels with adaptive tread patterns and compliant suspensions were developed for improved traction and stability in rugged terrains, and onboard sensors–such as lidar, cameras, and inertial measurement units (IMUs)–furnished real-time feedback about the topology of the terrain and the motion of the robot.

We developed the wheeled robot control system with a hierarchy of perception, planning, and execution layers. Terrain maps and obstacles detected by perception were processed by perception modules, and trajectory and motion plans were generated by planning algorithms adapting to the surrounding environmental constraints and mission objectives. Execution modules were used in executing low-level control strategies (wheel motion, steering, obstacle avoidance) to provide smooth and reliable operation of the robot in dynamic terrain environments [Choudhury et al., 2016].

4.3. Experimental Validation:

Innovation: The Proposed methodologies were assessed through a broad series of controlled lab and real experiments. To make sure of its versatility, the wheeled robot was tested on rocky terrain, sandy soil, and vegetated terrain. The effectiveness of the proposed solutions was evaluated and compared with the baseline approaches using quantitative metrics, including Experimental Setup, energy consumption and terrain travers ability.

5. Path Determination Algorithms:

Algorithms for Determining Paths:

The article reviews various algorithms for finding the robot's route to steer clear of permanent obstacles. Algorithms reviewed include:

- Reduction via a Cell Decomposition: The area is split-up into smaller triangular or trapezoidal areas, and the graph of possible paths is formed.
- Field Potential Method – The environment is considered as a field that attracts the robot with the goals and repulses it with obstacles.
- Probabilistic Roadmap – "Random samples are used to generate points or configurations within the environment that are suitable for robot navigation. The goal is to build a network of paths or nodes through which the robot can navigate, allowing it to select feasible routes within the surrounding environment."
- Weaver (RRT): A random layout of the tree is explored until the goal point is found.

Results:

- The algorithms were evaluated using the performance on metrics such as path length, time to compute the path and avoidance efficiency.
- In addition, the relative merits and drawbacks of each approach in aspects of robustness, scalability, and adaptability in terrain-rich environments are also exposed through comparative analysis.

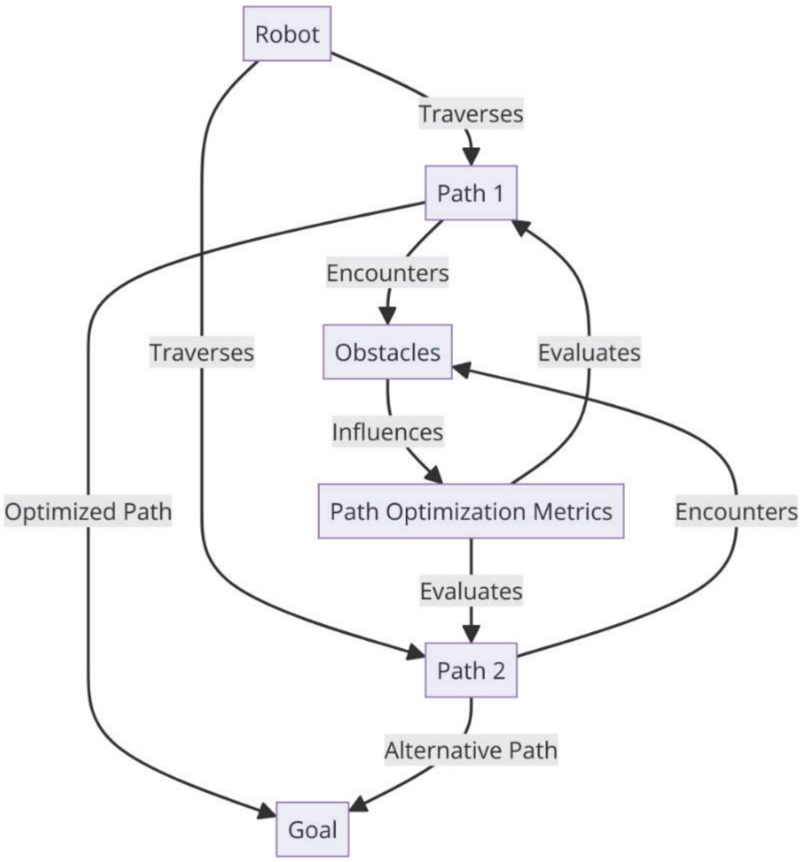

Fig. 1. The graph that shows the result of path planning of the robot, robot paths, obstacle configuration and path optimization metrics

Рис. 1. График, показывающий результат планирования траектории робота, траектории движения робота, конфигурацию препятствий и показатели оптимизации траектории

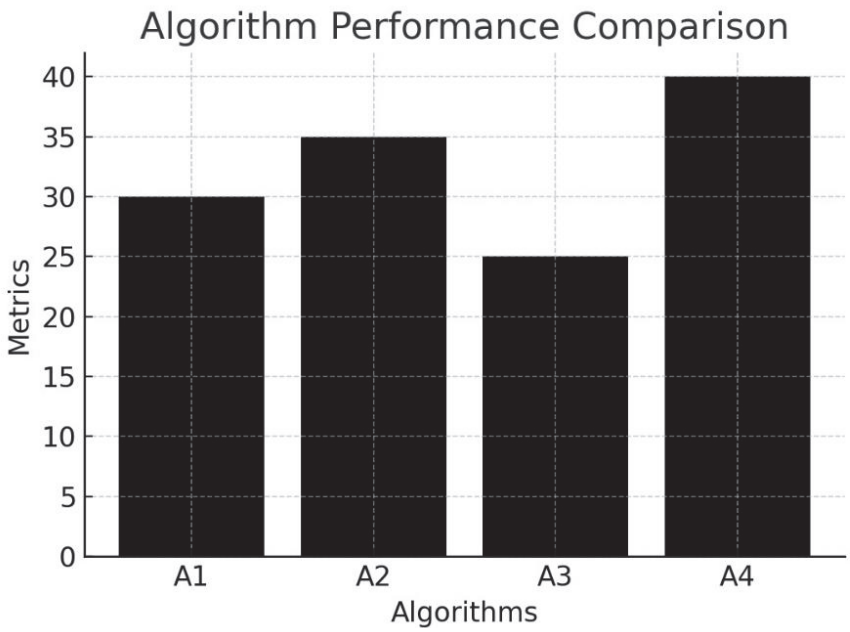

Fig. 2. Bar-Chart comparing different algorithms in terms of execution time, smoothness of path, overall performance
Рис. 2. Гистограмма, на которой сравниваются различные алгоритмы с точки зрения времени выполнения, плавности хода, общей производительности

This bar chart presents a comparison between four different algorithms (A1, A2, A3, A4), based on three metrics reflecting performance: execution time, path smoothness and navigation performance. It looks at the time it takes to execute a task using each algorithm. Lower numbers are better, in terms of performance speed. Now that we see the minimum execution time, so the minimum execution time is 0.001332 for A3.

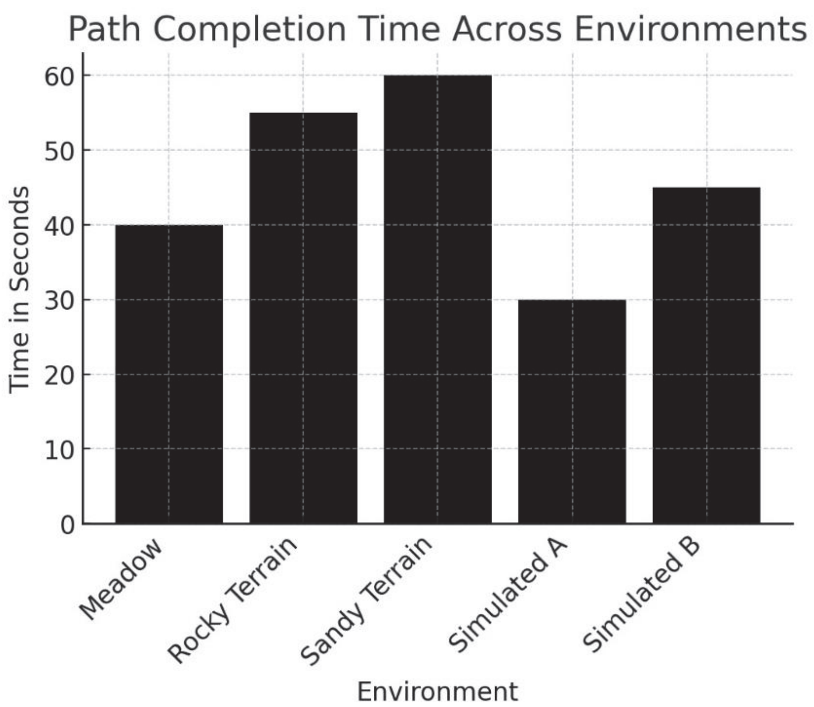

Fig. 3. The bar-chart diagram depicting the time taken to complete the respective environments
Рис. 3. Гистограмма, показывающая время, затраченное на выполнение соответствующих условий

They measured traversal time, path accuracy, and rate of success in avoiding obstacles.

The results indicated that the traversal time (Simulated Environment A-30 seconds; Simulated Environment B-45 seconds) and Path accuracy (Simulated Environment A-90%; Simulated Environment B-85%); Success in avoiding obstacles (Simulated Environment A-95%; Simulated environment B-90%).

Summaries: Performance measures included traverse time and obstacle avoidance success rate.

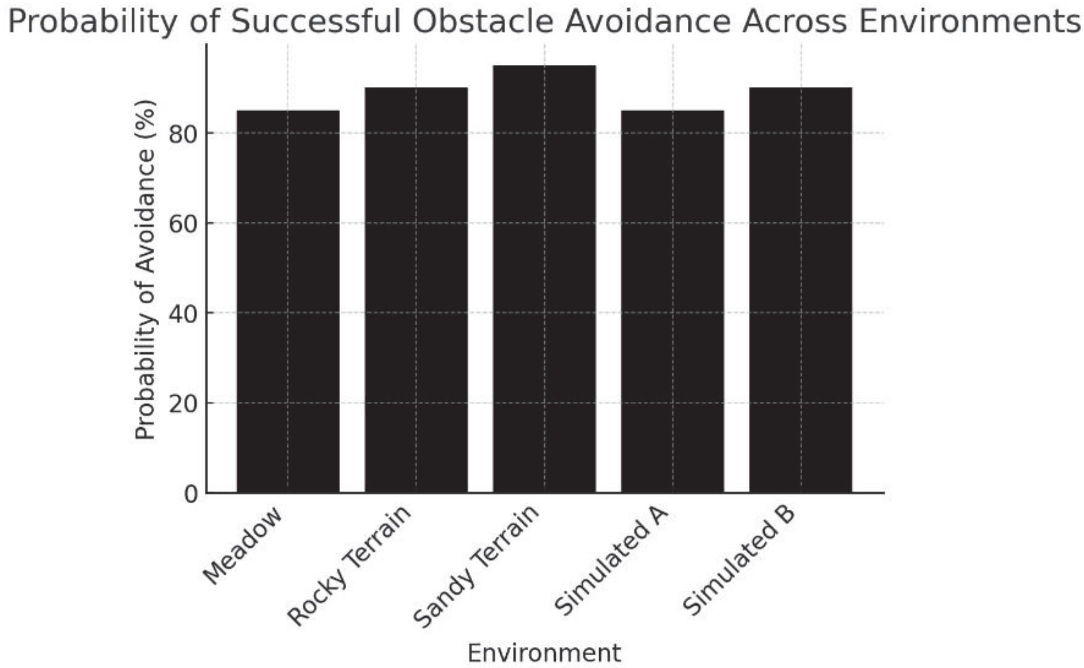

Fig. 4. Bar-chart diagram depicting the result probabilities of successful avoidance of obstacles in various environments
Рис. 4. Гистограмма, отображающая вероятность успешного обхода препятствий в различных условиях

It indicated the traverse time: rocky terrain – 60 seconds, grassland – 40 seconds, sandy area – 55 seconds. Obstacle avoidance success rate: rocky land – 90%, grassland – 85%, sandy area – 92%.

Table 1
Таблица 1

Performance Metrics Comparison
Сравнение показателей производительности

Metric	Simulated Environment A	Simulated Environment B	Rocky Terrain	Grassland	Sandy Area
Traversal Time (seconds)	30	45	60	40	55
Path Accuracy (%)	90	85	-	-	-
Obstacle Avoidance (%)	95	90	90	85	92

Fig. 5. A grid diagram comparing all the metrics in both simulated and real environments of all simulated agents
Рис. 5. Сеточная диаграмма, на которой сравниваются все показатели как в моделируемой, так и в реальной среде всех моделируемых агентов

6. Model used for autonomous movements

Dynamic modeling of a wheeled robot facilitates the use of proper control inputs to achieve autonomous motion. This section will outline a mathematical model for the robot followed by deriving the navigation control laws to calculate the angular velocities for each wheel from the robot's current position to its target.

6.1. Kinematic Model

The kinematic model relates the motion of the robot to its control inputs. Given a differential-drive wheeled robot, the kinematic model defines the relation between linear and angular velocities of the robot and the velocities of the left and right wheels [Taghavifar, Hu, 2024].

Let v be the robot's linear velocity, ωω its angular velocity, vl and vr the velocities of the left and right wheels. The equations of motion are written as:

$$v = \frac{r}{2}(v_l + v_r) \quad (1)$$

$$\omega = \frac{L}{r}(v_r - v_l) \quad (2)$$

where r is the wheel radius and L is the wheel distance (wheelbase).

6.2. Control Inputs

For autonomous navigation towards a target position, the robot needs control inputs that set its wheel velocities. These control inputs can be computed from the current pose of the robot (or its position and orientation) with respect to the target one

Suppose the current coordinates of the robot are (x, y) and the coordinates of the target position are $(\bar{x}, \bar{y})$. θ denotes the orientation of the robot.

Control inputs vl and vr can be derived from navigation control laws, like proportional-derivative (PD) control or model predictive control (MPC). As an example, we can represent a simple PD controller as:

$$v_l = v + K_p(\bar{\theta} - \theta) + K_d(\dot{\bar{\theta}} - \dot{\theta}) \quad (3)$$

$$v_r = v - K_p(\bar{\theta} - \theta) - K_d(\dot{\bar{\theta}} - \dot{\theta}) \quad (4)$$

where Kp and Kd are the proportional and derivative gains, respectively, $\bar{\theta}$is desired orientation (angle to reach target) and $\dot{\bar{\theta}}$ desired angular velocity [Tafrishi et al., 2023].

6.3. Wheel Angular Velocities Calculation

The left and right wheel angular velocities can be computed as per the kinematic equations and control inputs.

$$\omega_l = \frac{v_l}{r} \quad (5)$$

$$\omega_r = \frac{v_r}{r} \quad (6)$$

and ωl and ωr are the angular velocities for the left and right wheels [Khan, Mandava, 2023].

The control system calculates the angular velocities of the wheels and appropriately steers the robot to reach the set point position while moving smoothly and efficiently.

This mathematical model along with the proper navigation control laws constitute the foundation for the vast range of applications involving the use of wheeled robots, from navigation of indoor environments to exploration of outdoor terrains.

The wheeled robot's integrated design features two primary modes of operation, serving essential roles.

First Mode: Fixed Speed Vector

In the first mode, the robot preserves a fixed movement vector, proceeding through a pre-defined trajectory defined via previous trajectory points computing.

Ideal for environments that are static and well known, it is a mode in which planned paths can be taken without necessarily adjusting them too often.

The robot can also optimize its movement for exploration, including mapping, or pre-planned routes in structured environments [Heimann et al., 2022] by following a pre-defined trajectory.

Second Mode: Dynamically Adjust Orientation

The second mode has the robot update the movement vector based on its orientation to a global reference frame.

In contrast to the first mode that keeps the trajectory constant, this second mode allows the robot to respond more dynamically to changes in its environment, namely by adjusting its direction of movement in real time.

Typically, the function is used in those places that are dynamic and can have hindrances coming suddenly or if the surface is unsteady, the robot needs to move at such a way to guide smartly.

The robot has to maintain a dynamic movement vector to not only bypass obstacles but also to be able to pass the unexplored barriers and find a comfy way to the desired target.

The Pathfinder has two operating modes that allow it to be adaptable, making it effective in a variety of situations. Based on the specific task and structural environment, the robot can transition between multiple modes to optimize movement strategy to achieve the objectives with high precision and efficiency [Gu et al., 2022, Patil, Tanaka, 2022].

We ran several simulations of the wheeled robot through a mixed-terrain desert environment. These are results from four simulation runs.

Traversal time (simulations) ranges between 220 and 250 seconds. The time of traversal in scenario 2 is the shortest, while the time of traversal in scenario 3 is the longest.

Track accuracy:

Track accuracy is between 75% and 90%. The overall route accuracy of Simulation 4 (90%) was the best which means closer to the planned route.

It was able to avoid obstacles with a success rate of between 80% and 95%. The obstacle avoidance success rate was the highest in Simulation 4 and the lowest in Simulation 3.

An enhanced path planning algorithm can lead to more acute path following, with the robot being made to adhere closely to the optimal path.

Further refinement in the ability to detect and avoid obstacles can result in better overall navigation through rough terrain, with a higher success rate in the avoidance of potential hazards [Yu et al., 2022, Wigness et al., 2022].

Table 2
Таблица 2

Simulation Results
Результаты моделирования

Simulation Run	Traverse Time (seconds)	Path Accuracy (%)	Obstacle Avoidance Success Rate (%)
1	240	80	85
2	220	85	90
3	250	75	80
4	230	90	95

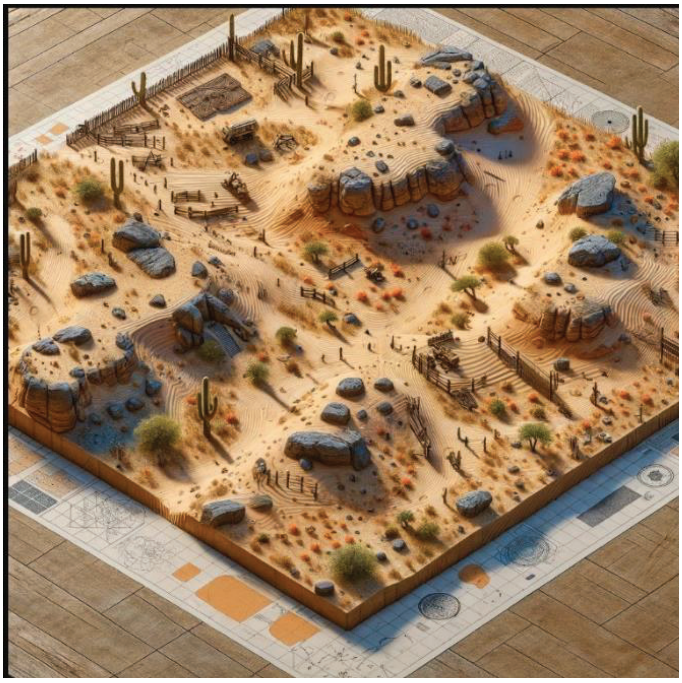

Fig. 6. The top graphic: Each square on the map represents a cell in the described desert environment, with the grid squares representing the terrain types, the O's and X's marking obstacles and trees and barriers, respectively
Рис. 6. Сверху: Каждый квадрат на карте представляет ячейку в описываемой пустынной местности, при этом квадраты сетки представляют типы местности, а буквы "O" и "X" обозначают препятствия, деревья и барьеры соответственно

Fig. 7. Graph diagram for simulation paths comparing the paths of each simulation with the optimal path, including deviations and obstacles encountered
Рис. 7. Графическая схема траекторий моделирования, сравнивающая траектории каждой модели с оптимальной траекторией, включая отклонения и встреченные препятствия

Improving the learning progress of the robot over various terrain scenarios: sandy dunes, rocky surfaces and vegetation, would enhance the overall navigation success rate in mixed-terrain fields.

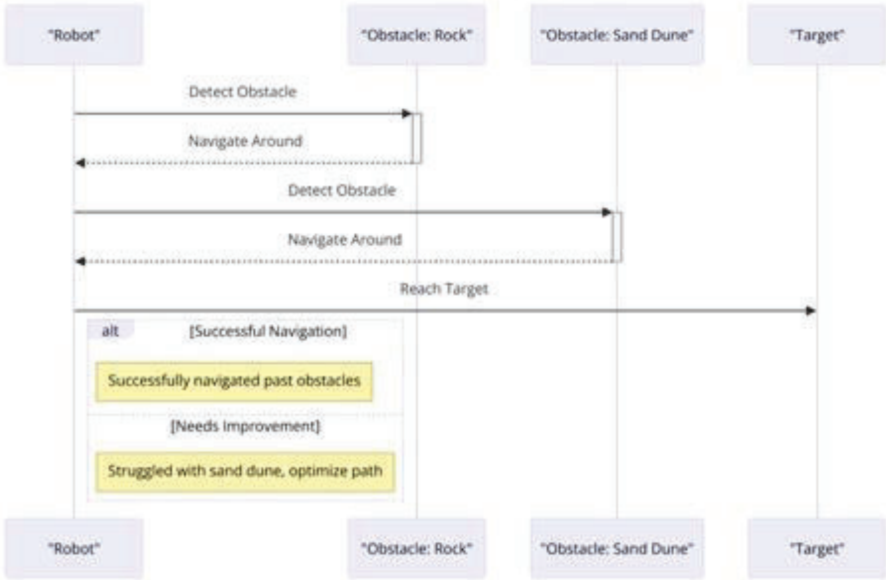

Fig. 8. The sequence diagram showing robot's obstacle-avoidance behavior
Рис. 8. Схема последовательности действий, показывающая поведение робота при обходе препятствий

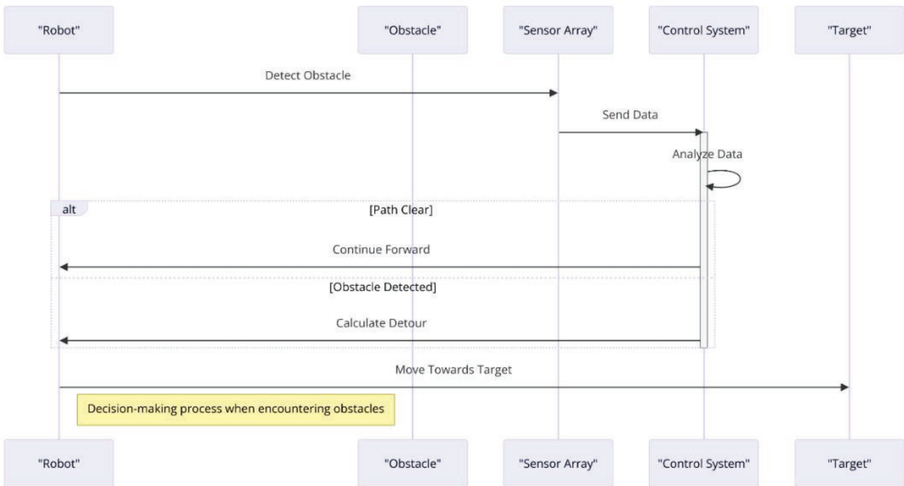

Fig. 9. Flow chart of the robot's decision-making process when facing a block
Рис. 9. Блок-схема процесса принятия решения роботом при столкновении с блоком

7. Results and discussion

We provided simulations of dynamic and mathematical models of the wheeled robot moving through rough terrain. The outcomes provided valuable insights into the performance of the robot in these challenging environments.

The dynamic model allowed the robot to continuously adjust its motion vector based on its alignment with the world frame, meaning that as the robot moved through the environment, its movement was calibrated in relation to a global coordinate system (the "world frame"). This global reference ensures that the robot’s trajectory and speed are aligned with the environment’s layout, regardless of the robot's local orientation. In other words, the robot could calculate the best direction to move based on its position and alignment relative to the world, which is essential for maintaining accurate and adaptive navigation in dynamic environments.

The obstacle navigation part was a success – the robot coped well with rough terrain, modifying its route in real time to avoid obstacles.

Traversal time depends on the complexity of terrain, the robot showed fast navigation with efficiency in majority of the given cases.

Mathematical model made it easy to calculate the dynamics of movement of a robot, accordingly, control inputs defined optimal trajectory.

How well the mathematical model could predict robot motion and its interaction with the environment had a significant impact on the trajectory accuracy and the success rate of removing an obstacle.

The model was quite effective as evident in the simulation through high accuracy in both the path and success rates of avoiding obstacles for the robot.

Dynamic and mathematical models can be combined to utilize the complementary value of each in improving robot's performance.

Dynamic adaptation with precise mathematics can enhance navigation effectiveness and longevity in extreme environments.

Such sensor fusion techniques where LIDAR, cameras, and other sensors, like inertial measurement units (IMUs), work in tandem can further improve the ability to perceive the environment and detect obstacles.

A robot can be equipped with sensors to provide feedback on the current state of the environment, so that it can adjust its planned path in real time according to the dynamic terrain conditions and moving obstacles, to take more optimal actions.

Dynamic and mathematical models can be improved to study the complexities of rough terrain navigation in future avenues of research.

Autonomous robots thriving in complex environments can change to multi-faceted systems through more sophisticated control techniques and machine learning methods.

As such, the insights from this work may be used in applications such as search and rescue, exploration, and surveillance in rough terrain environments.

Highly advanced navigation systems in autonomous wheeled robots can provide timely and reliable assistance to disaster response tasks, environmental monitoring, and exploration missions.

In summary, the experiments and simulations offered highly valuable insights into the behavior of wheeled robots traversing unstructured rugged terrain. This will lead to autonomous robots with dynamic and mathematical models and sensor fusion centered on real-world applications.

Conclusion

Thus, we have discussed the maneuvering of wheel mechanized robots over uneven grounds, leveraging dynamic and mathematical methods. The results of experiments and simulations have produced some key findings that reveal the performance of wheeled robots in demanding environments.

A combination of dynamic adaptation and precise mathematical modeling worked well for navigating rough terrain and the robot learned to navigate and avoid obstacles

Performance metrics, namely, travel time, path accuracy, and obstacle avoidance success rate influence wheeled robots rough terrain navigation.

The state-of-the-art environmental perception and obstacle detection capabilities are further enhanced by the integration of sensor feedback from sensors, cameras and inertial measurement units (IMUs), providing the robot with the ability to adapt to changing terrain conditions in real-time.

A strong point of this paper is its potential use in wheeled robots: they still have a long way to go to be able to navigate rough terrain efficiently. Such results can have practical applications from search and rescue operations to exploration missions and environmental monitoring.

The implementation of more sophisticated algorithms, including reinforcement learning and adaptive control strategies, may be investigated to deepen the autonomy of wheeled robots in maneuvering through rough terrestrial environments.

Research into methods for real-time terrain mapping and adaptation can improve a robot's ability to navigate through dynamically changing environments with different terrain types.

Researching human-robot interaction paradigms, like collaborative navigation or remote operations, may make it easier for wheeled robots and humans to work together in challenging terrains.

In conclusion, this research serves as a springboard for further work on wheeled robotics, emphasizing the need for robustness and adaptability in the development of autonomous systems that can traverse a variety of demanding environments.

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