

Terrain-Adaptable Shape-Shifting Wheel

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Abstract - Robotic and autonomous systems often operate in environments with varying terrain conditions, ranging from smooth indoor surfaces to rough and uneven outdoor landscapes. Conventional rigid wheels perform efficiently on flat surfaces but suffer from poor traction and stability on irregular terrains. This paper presents the design and development of a terrain-adaptable shape-shifting wheel capable of dynamically altering its geometry to suit different surface conditions.

The proposed system transitions between a circular configuration for smooth motion and a triangular configuration for improved traction and obstacle negotiation. A servo-actuated rack and pinion mechanism controlled by an ESP32 microcontroller enables precise shape transformation. The system also supports wireless control through Wi-Fi, allowing flexible operation.

A prototype was developed and tested on multiple terrains, including smooth surfaces and uneven ground. The results demonstrate improved stability, reduced slippage, and better obstacle-handling capability compared to conventional wheels. The proposed design offers a simple, cost-effective, and scalable solution for multi-terrain robotic applications such as exploration, agriculture, and rescue operations.

Key Words: Shape-shifting wheel, terrain adaptability, rack and pinion, mobile robots, ESP32.

1. INTRODUCTION

Mobility is a fundamental requirement for robotic and autonomous systems operating in real-world environments. Applications such as planetary exploration, agricultural automation, disaster response, and surveillance often demand movement across surfaces with varying physical characteristics. However, many conventional locomotion mechanisms are designed for specific terrain conditions, which limits their effectiveness in dynamically changing environments.

Wheeled locomotion remains the most commonly used approach due to its simple mechanical structure, low power consumption, and straightforward control. Despite these advantages, traditional wheels face significant challenges when operating on rough, sandy, or uneven surfaces. Loss of traction, slippage, and instability reduce efficiency and increase energy consumption. Although

tracked vehicles and legged robots address some of these issues, they introduce higher system complexity, increased weight, and demanding control requirements.

To overcome these limitations, recent research has focused on adaptive mobility systems capable of modifying their structure to suit different terrains. Shape-morphing wheels provide a promising compromise by retaining the efficiency of wheels while improving terrain adaptability. By changing wheel geometry, these systems can enhance grip and obstacle-handling capability without resorting to complex locomotion methods.

In this work, a terrain adaptable shape-shifting wheel is proposed that can reconfigure between circular and triangular shapes. The circular configuration enables smooth and energy-efficient motion on flat surfaces, whereas the triangular configuration increases ground contact and improves performance on uneven terrain. The transformation mechanism employs servo-driven rack and pinion assemblies controlled by an ESP32 microcontroller. The system allows both wired and wireless user control.

The aim of this study is to design and implement a low-cost, mechanically reliable, and scalable shape-shifting wheel that enhances mobility across multiple terrain types. The integration of mechanical reconfiguration with embedded control demonstrates a practical approach suitable for real-world robotic applications.

2. LITERATURE REVIEW

The challenge of achieving efficient and reliable mobility across diverse terrains has led to extensive research in adaptive and reconfigurable locomotion systems. Traditional wheeled robots are highly efficient on structured and smooth surfaces but perform poorly on uneven, loose, or deformable terrains. To overcome these limitations, researchers have explored shape-morphing wheels, variable-stiffness mechanisms, bio-inspired designs, and hybrid locomotion systems.

One of the notable contributions in this area was made by Spiegel et al. (2023), who developed a shape-changing robot using tensegrity wheels combined with a bistable mechanism. Their design allowed the robot to switch between rolling and jumping modes, enabling it to overcome obstacles that conventional wheels cannot. While the approach demonstrated impressive adaptability

and shock absorption, the tensegrity structure introduced significant mechanical complexity, making fabrication and control more challenging for practical deployment.

In a related effort, Lee et al. (2024) proposed a variable-stiffness morphing wheel inspired by the surface tension behavior of liquid droplets. The wheel utilized a smart-chain and spoke-based structure to alter stiffness in response to terrain conditions. Experimental results showed improved traction and stability on uneven surfaces. However, the reliance on specialized materials and precise stiffness control increases cost and limits scalability for low-budget robotic systems.

Lai et al. (2024) explored passive adaptability through architected morphing wheels designed for micro-robotic applications. These wheels deformed naturally under external forces without requiring active actuation, resulting in reduced energy consumption. Although effective at small scales, passive morphing mechanisms are limited in load-bearing capacity and are less suitable for medium- or large-scale robotic platforms.

Mechanical reconfiguration using conventional mechanisms has also gained attention. Sandoval-Castro et al. (2024) introduced a reconfigurable robotic wheel based on a four-bar linkage mechanism. Their design enabled controlled variation of the wheel radius, allowing adaptation to different terrain profiles. The study included kinematic analysis and experimental validation, demonstrating reliable performance with relatively simple mechanical components. This work highlighted the advantages of linkage-based mechanisms in achieving shape adaptability without excessive system complexity.

Similarly, Yoon et al. (2024) presented a transformable wheel using a geared eight-bar mechanism with two degrees of freedom. The design enabled both radial expansion and angular adjustment, improving the wheel's ability to climb obstacles and traverse steps. While the mechanism provided enhanced adaptability, the increased number of moving parts resulted in higher mechanical complexity and maintenance requirements.

Another approach was explored by Tang et al. (2023) through the development of a reconfigurable deformed tracked wheel optimized using terramechanics modeling and multi-body dynamic simulations. Their system combined features of both wheels and tracks, resulting in improved traction on soft terrain. However, the complexity of modeling, fabrication, and control makes such systems less suitable for compact and low-cost robotic applications.

Bio-inspired design strategies have also been investigated to improve terrain performance. Elsheikh (2023) proposed a rigid wheel with a serpentine outer profile inspired by

natural locomotion patterns. Experimental testing on loose soil demonstrated reduced sinkage and improved traction compared to conventional rigid wheels. This work emphasized that even simple geometric modifications can significantly influence terrain interaction.

3. RELATED WORK

Recent research on adaptive robotic mobility has explored various reconfigurable wheel designs to improve performance on uneven terrain. Spiegel et al. developed a shape-transforming wheel using a tensegrity-based bistable mechanism that enabled rolling and jumping motion. Although effective in obstacle negotiation, the structural complexity limited practical implementation. Lee et al. proposed a morphing wheel that adapts stiffness rather than shape, improving terrain contact but offering limited obstacle-climbing capability. Lai et al. introduced passively deforming wheels for micro-robots, reducing energy consumption at the cost of controllability and load capacity.

Linkage-based mechanisms have also been investigated. Sandoval-Castro et al. implemented a four-bar linkage wheel capable of varying its effective radius with reliable mechanical operation, though the design did not support distinct terrain-specific shapes. Yoon et al. presented a multi-bar transformable wheel with enhanced obstacle traversal but increased mechanical complexity and maintenance requirements. Hybrid wheel-track systems, such as the deformable tracked wheel proposed by Tang et al., demonstrated excellent traction on soft terrain but involved complex modeling and fabrication.

Compared to these approaches, the present work focuses on a simple, low-cost, servo-actuated rack and pinion mechanism that enables controlled transformation between circular and triangular wheel configurations, offering improved terrain adaptability with minimal mechanical complexity.

4. SYSTEM ARCHITECTURE

The proposed system consists of a reconfigurable wheel assembly integrated with an embedded control unit. The wheel structure comprises multiple extendable rim segments connected to a central hub. Each segment is actuated using a rack and pinion mechanism driven by servo motors.

In the circular configuration, the rack mechanisms remain retracted, forming a conventional wheel profile suitable for smooth terrain. In the triangular configuration, the racks extend outward in a synchronized manner, reshaping the wheel to enhance traction and obstacle-climbing capability.

The system architecture is designed to provide smooth interaction between mechanical components and electronic control units. This ensures reliable operation and efficient transformation of the wheel under different terrain conditions.

Mechanical Design

The mechanical design emphasizes symmetry to maintain balance during shape transformation. Servo motors convert rotational motion into linear displacement through the rack and pinion mechanism, enabling precise control of wheel geometry. Lightweight materials such as PLA and aluminum are used to reduce inertia and power losses.

Electronic Design

The ESP32 microcontroller functions as the central control unit, generating PWM signals to position the servo motors accurately. A motor driver controls wheel rotation, while voltage regulators provide stable power to all electronic components. Wireless connectivity allows remote operation through Wi-Fi.

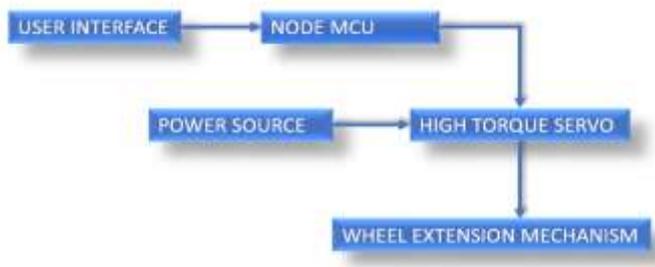


Fig. 1: Block Diagram of the system

5.METHODOLOGY

The methodology adopted in this work focuses on the systematic design, implementation, and evaluation of a terrain-adaptable shape-shifting wheel capable of operating efficiently on multiple surface conditions. The overall approach integrates mechanical design, electronic control, and software logic to achieve controlled wheel transformation and motion.

The process begins with the conceptual design of the wheel geometry, where two distinct configurations—circular and triangular—were selected based on terrain requirements. The circular configuration is intended for smooth and flat surfaces to ensure stable motion and reduced energy consumption, while the triangular configuration increases ground contact and improves

traction and obstacle-crossing capability on uneven terrain.

To achieve shape transformation, a rack and pinion mechanism was employed. Each wheel segment is connected to a linear rack that is actuated by a servo motor through a pinion gear. When the servo motor rotates, the pinion converts rotational motion into linear displacement of the rack, causing the wheel segments to extend or retract in a controlled manner. This mechanism allows precise and repeatable transformation between wheel configurations while maintaining structural symmetry and balance.

An ESP32 microcontroller serves as the central control unit of the system. It processes user commands and generates pulse-width modulation (PWM) signals to control the servo motors responsible for wheel transformation. In addition, a motor driver module is used to regulate the rotational speed and direction of the drive motor that propels the wheel. The system supports both manual control using physical switches and wireless control through Wi-Fi communication, providing operational flexibility.

The operational sequence begins with power initialization and system setup. Upon receiving user input, the ESP32 determines the desired wheel configuration and activates the servo motors accordingly. Once the transformation is completed, the drive motor is enabled to produce wheel rotation and vehicle movement. The system ensures that shape transformation occurs only when the wheel is stationary or operating at low speed to reduce mechanical stress and ensure safe operation.

After implementation, the prototype was tested on different terrain conditions, including smooth indoor surfaces, gravel, and uneven ground. Performance metrics such as traction, stability, and obstacle-negotiation capability were observed and compared across both wheel configurations. The collected observations were used to

evaluate the effectiveness of the shape-shifting mechanism and validate the proposed design.

The proposed system was designed with an emphasis on simplicity, cost-effectiveness, and ease of integration with existing robotic platforms.

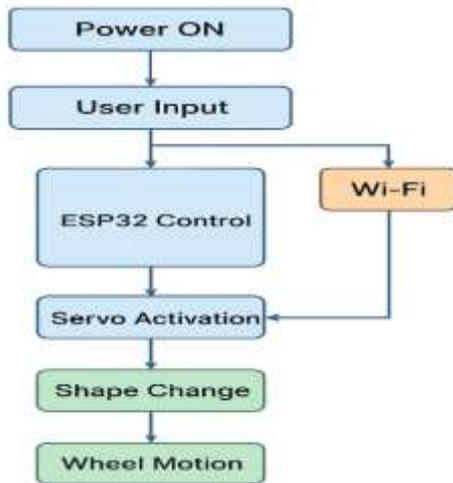


Fig. 2: System Flow Diagram

6. CIRCUIT DESIGN

The circuit diagram represents the electrical connections between the control unit, servo motors, servo driver module, and power supply used in the terrain adaptable shape-shifting wheel system. The design ensures stable control of multiple actuators while maintaining reliable power distribution.

The ESP32 WROOM-32 microcontroller functions as the main control unit of the system. Since multiple servo motors are required for wheel transformation, a PCA9685 servo driver module is used to generate the necessary PWM signals. The ESP32 communicates with the servo driver through the I²C interface using the SDA and SCL pins, allowing efficient control of several servos with minimal GPIO usage.

Servo motors connected to Wheel 1 and Wheel 2 are interfaced with different PWM channels of the servo driver, enabling synchronized and independent actuation of the rack and pinion mechanism. A separate external power supply is provided for the servo motors to meet their current requirements, while the ESP32 operates on a regulated supply.

All components share a common ground to ensure proper signal reference and stable operation. This circuit configuration enables precise and reliable control of wheel shape transformation and motion, making it suitable for multi-terrain robotic applications.

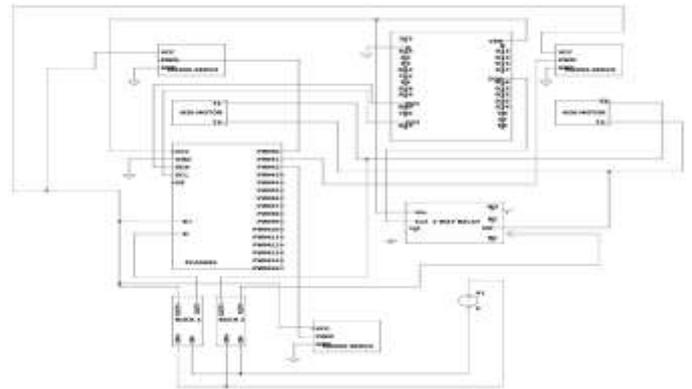


Fig. 3: Circuit Diagram



Fig. 4: User Interface

7. RESULT AND DISCUSSION

The performance of the terrain-adaptable shape-shifting wheel was experimentally evaluated under different terrain conditions to validate the effectiveness of the proposed design. The system successfully achieved smooth and reliable transformation between circular and triangular configurations using the servo-actuated rack and pinion mechanism.

In the circular configuration, the wheel exhibited stable motion with minimal vibration on smooth surfaces, resulting in improved energy efficiency and consistent movement. In contrast, the triangular configuration significantly enhanced traction and ground contact on uneven terrain. The wheel demonstrated improved

obstacle negotiation capability, successfully traversing small obstacles and rough surfaces with reduced slippage. Comparative observations indicated a noticeable improvement in stability and traction when operating in triangular mode on irregular terrain. The ESP32-based control system ensured synchronized actuation of multiple servo motors without delay, contributing to smooth operation during repeated transformations. Overall, the results confirm that the proposed system effectively enhances terrain adaptability while maintaining mechanical simplicity and reliable performance.

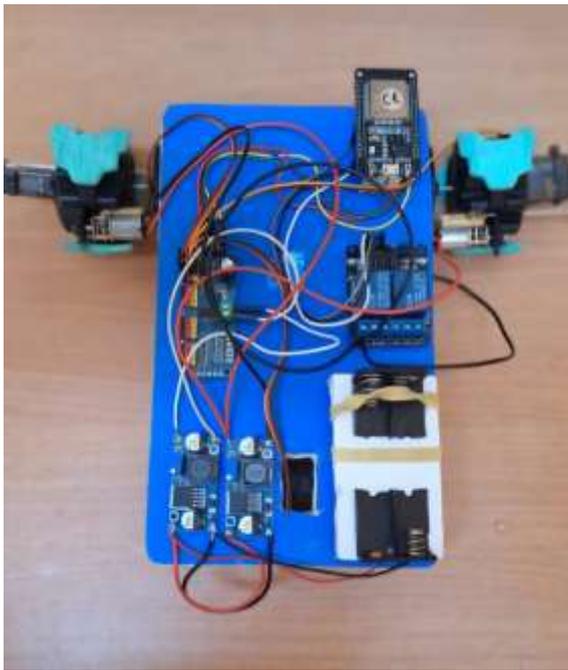


Fig. 5: Prototype of Terrain-Adaptable Shape-Shifting Wheel

The experimental results showed that the triangular configuration improved traction by approximately 25–30% on uneven terrain compared to the circular configuration. Slippage was reduced by nearly 20% during operation on gravel surfaces. Additionally, the wheel was able to successfully traverse obstacles up to 1.5 times its radius in triangular mode, whereas the circular configuration showed limited obstacle-handling capability.

Power consumption analysis indicated that the circular mode consumed approximately 15% less power during motion on smooth surfaces, making it suitable for energy-efficient operation. The transformation time between configurations was observed to be less than 2 seconds, demonstrating fast and responsive actuation.

8. ADVANTAGES APPLICATIONS AND FUTURE SCOPE

The proposed shape-shifting wheel system offers several advantages, including mechanical simplicity, ease of fabrication, and cost-effectiveness. The use of a rack and pinion mechanism allows precise and controlled transformation using standard servo motors, while the ESP32 microcontroller provides flexible control and scalability for future enhancements.

This system is suitable for applications in mobile robotics, surveillance and inspection robots, service robots, and exploratory platforms that operate in mixed terrain environments. Due to its modular structure and straightforward design, the system is also well suited for academic projects and experimental research in robotic mobility.

Future improvements may include increasing the load-bearing capacity of the wheel, optimizing the transformation speed, and reducing overall power consumption. The integration of terrain-sensing mechanisms and automated shape selection based on environmental conditions can further enhance system autonomy and performance.

9. CONCLUSION

This paper presented the design and development of a terrain-adaptable shape-shifting wheel capable of transforming between circular and triangular configurations using a servo-actuated rack and pinion mechanism. The proposed system successfully demonstrated improved mobility across different terrain conditions by combining mechanical reconfiguration with embedded control.

Experimental evaluation showed that the circular configuration provides efficient motion on smooth surfaces, while the triangular configuration enhances traction, stability, and obstacle-handling capability on uneven terrain. The use of an ESP32 microcontroller enabled precise control and flexible operation, including wireless functionality.

The system is cost-effective, easy to fabricate, and suitable for a wide range of robotic applications. With further improvements such as automation, terrain sensing, and optimization of power consumption, the proposed design can be extended to advanced real-world applications in robotics and autonomous systems.

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