Research Article

Development and Control Method for a Six-Wheeled Robot with a Bogie Structure

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Abstract: *This study focuses on the development and optimization of a six-wheeled Rocker-Bogie Robot designed for efficient stair navigation in diverse environments. The robot's design incorporates critical parameters, including wheel placement, motor torque distribution, and suspension geometry, to enhance stability and adaptability. A systematic iterative process improved the robot's ability to overcome obstacles such as stairs with dimensions of 6 × 30 cm and 8 × 34 cm. The methodology integrates kinematic constraints, contact angle analysis, and motor control optimization to refine performance. Experimental results validated the robot's capability to ascend and descend stairs while maintaining stability, demonstrating its potential for real-world applications in delivery, healthcare, and maintenance. This work contributes to advancing cost-effective and reliable stair-climbing robotics, paving the way for further enhancements in service robotics for complex indoor and outdoor terrains.*

Keywords: Six-wheeled Robot; Rocker-Bogie Structure; Stair-Climbing Strategy.

DOI: 10.5281/zenodo.14854530

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1. INTRODUCTION

Stair-climbing is one of the most challenging tasks for indoor service robots. During the 2015 DARPA Robotics Challenge (DRC), stair-climbing was the final task, with only 30% of the robots completing it, despite years of robotics research. The fastest recorded time for a robot to ascend four steps is about 4 seconds—approximately 1 second per step—significantly slower than human capabilities (Krotkov et al., 2018). The diverse characteristics of stairs, including variations in step height, tread length, materials, shapes, and environmental factors like handrails, complicate the design of reliable stair-climbing robots. To overcome these challenges, robots require carefully designed locomotion systems, robust control methods, and effective stair-detection strategies to ensure stability and speed across different conditions.

Legged robots, such as humanoid and quadruped designs, are considered ideal for stair-climbing due to their inherent adaptability. Notable examples include Atlas and Spot from Boston Dynamics, which have demonstrated impressive stair-climbing performance comparable to or even exceeding that of humans (VRABIE, 2024). However, these robots necessitate advanced sensors, high-power motors, and complex control systems, resulting in high costs and limiting their practical applications due to safety concerns. To explore simpler and more cost-effective solutions, researchers have investigated alternative mechanisms such as modified tracked and wheeled designs. Examples include PackBot for reconnaissance (Yamauchi, 2004) and Scalevo for assisting individuals with disabilities (Verma et al., 2024). Recent innovations like wheel-legged and wheel-linkage mechanisms combine the mobility of wheels with the adaptability of legs to efficiently navigate obstacles like stairs (Kim et al., 2021). The success of a ground robot largely depends on its ability to traverse various terrains. Wheel traction systems perform well on smooth surfaces but struggle with obstacles or loose materials like sand; a wheel cannot surmount an obstacle taller than its radius. Tracked systems improve traction on loose terrains but consume more energy—a significant drawback for battery-operated robots.

This project focuses on developing a six-wheeled robot with a bogie structure aimed at addressing these limitations. The bogie design enhances adaptability by allowing the robot to maintain stability and effectively distribute its weight while climbing stairs or traversing uneven terrain. This approach merges the efficiency of wheel-based systems with superior obstacle-climbing capabilities. By integrating efficient control strategies and robust mechanical design, this six-wheeled bogie robot is engineered to handle diverse indoor and outdoor conditions, positioning it as a versatile option for service applications (Park et al., 2024).

1.1 Completeness of Product

The development of the robot currently stands at Technology Readiness Level (TRL) 5-6, signifying that it has been validated in a controlled environment and is advancing toward operational readiness. Through iterative prototyping, the system has transitioned from concept validation to practical application, ensuring that its design meets functional and performance requirements necessary for real-world use. Each iteration has played a critical role in addressing reliability of the robot.The robot has undergone three distinct stages of prototyping, each focused on resolving key issues related to its functionality. These include optimizing motor torque to enhance lifting capabilities, reducing weight to improve mobility, addressing traction issues for stable movement , and integrating sensors for precise environmental awareness. With every iteration, significant progress has been made in refining the design and improving the robot's operational performance.

To ensure reliability in practical scenarios, the robot has been rigorously tested across various terrains, including staircases, to stimulate real-world conditions. The design process has accounted for challenges such as uneven surfaces and the need for robust laod-bearing capabilities. This comprehensive testing and validation have been integral to enhancing the robot's functionality and ensuring its adaptability to diverse operational environments. Future development efforts will focus on achieving higher TRL levels by refining the robot's components and incorporating advanced sensor technologies. These improvements aim to enhance its functionality and expand its usability to broader applications, such as deployment in public spaces and delivery services. By addressing these areas, the robot is expected to achieve greater versatility and readiness for widespread adoption.

1.2 Novelty

The robot introduces several novel features that set it apart from conventional designs. Foremost among these is its unique six-wheeled bogie structure, which combines the high mobility typically associated with wheels with enhanced adaptability for navigating stairs and uneven terrains. This innovative configuration represents a significant improvemnet ove rtraditional mobility systems, addressing challenges often encountered in such environments. Another notable aspect of the robot;s novelty lies in its resource efficiency. It employs cost-effective alternative sensors and materials without sacrificing performance, demonstrating an innovative approach to optimizing resources. This balance of affordability and functionality not only enhances the robot's practicality but also widens its potential accessibility to users with limited budgets. Additionally, the design effectively tackles common problems faced by mobility robots. Specifically, it addresses critical issues such as low torque, instability on stairs, and traction inefficiencies. By resolving these challenges, the robot enhances reliability and ensures smoother performance in diverse and demanding operational conditions.

Moreover, the robot's focus on accessibility is a defining feature. It has been deliberately designed to bridge the gap between cutting-edge robotics and practical, affordable solutions to real-world mobility challenges. This emphasis on creating an accessible technology positions the robot as a solution that can benefit a broader audience, extending its utility beyond niche applications. Finally, the robot's versality underscores its novel contributions. It is capable of functioning in a wide range of applications, including home assistance, delivery services, and public accessibility. This adaptability ensures that the robot can effectively meet the demands of various real-world scenarios, making it a valuable tool in diverse contexts.

1.3 Commercialization

The robot is specifically targeted at elderly individuals, caregivers, and people with mobility challenges, who collectively represent a substantial demand for accessibility solutions. This demographic highlights a critical need for innovative technologies that can enhance independence and improve quality of life. By addressing their specific challenges, the robot is positioned to meet a pressing societal demand. In terms of applications, the robot offers a broad scope of use cases. It is designed for home assistance, delivery services, and public accessibility enhancements, making it highly versatile. These applications not only demonstrate its utility in individual and domestic settings, but also its potential to contribute to larger-scale public infrastructure improvements.

Moreover, cost-effective production is a key feature of the robot's design strategy. Through the refinement of components and the use of affordable materials, productions costs can be minimized without compromising quality or performance. This approach ensures that the robot remains accessible to a larger marker, enhancing its appeal to consumers who may be deterred by the high costs typically associated with advanced robotics. Another significant strength lies in the robot's scalability. Its modular design allows for easy adaptation to different terrains and tasks, enabling it to cater to a wide range of industries and environments. This flexibility ensures that the robot remains relevant across diverse operational contexts, further increasing its market potential. Finally, the robot's competitive advantage lies in its unique combination of affordability, practicality, and adaptability. Unlike high-cost robots designed for niche markets, this robot offers a more balanced approach, providing effective solutions at a price point accessible to a broader audience. This distinctive combination positions it as a standout option in the growing field of mobility robotics.

1.4 Academic Contribution

This project makes significant academic contributions to the field of robotics, particualrly in the area on stair-climbing and terrain-adaptive systems. By focusing on practical applications, its adds to the growing body of knowledge on mobility robotics, offering insights that bridge theoretical research and real-world implementation. This research not only advances the understanding of terrain-adaptive robotics but also highlights the importance of addressing accessibility challenges through innovative engineering solutions. One of the key contributions lies in the design innovations demonstrated by the robot. This project integrates essential mechanical design principles, such as weight optimization, torque efficiency, and adaptive traction systems, to overcome common mobility challenges. These advancements in design methodology can serve as a foundation for future robotic systems, pushing the boundaries of what is achievable in terrain-adaptive robotics.

Additionally, the project generates valuable experimental data, shedding light on technical and practical challenges in developing multi-functional, terrain-adaptive robots. By documenting the solutions employed to address these challenges, the project provides a comprehensive reference for researches and engineers working on similar technologies. This data is particularly valuable for informing the design and development of future mobility robots. Finally, the project has a meaningful educational impact, offering a robust learning platform for students and researchers. It enables the exploration of interdisciplinary applications of robotics, control systems, and mechanical engineering. By engaging with this project, learners can gain hands-on experience and a deeper understanding of the integration of theoretical concepts with practical design and implementation. Thus, the project not only contributes to research but also fosters the development of the next generation of engineers and innovators.

1.5 Design of Product

The design of the robot incorporates several innovative features that enhance its functionality and adaptibility to diverse environments. At the core of the design is a six-wheeled bogie system, which provides exceptional stability and adaptability across stairs and uneven terrains. This system effectively balances weight distribution and traction, ensuring optimal performance even in challenging conditions. A key focus of the design process is has been weight optimization. By developing a lightweight yet durable frame, the strain on the robot's motors is significantly reduced, addressing issues encountered during earlier prototypes. This optimization enhances the robot's overall efficiency and extends its operational lifespan. Traction has also been improved through the use of advanced wheel materials and configurations, which prevent slipping on smooth or inclined surfaces. These enhancements ensure reliable performance across a wide range of terrains, further bolstering the robot's adaptability.

The robot's integrated control system plays a crucial role in its ability to navigate stairs and obstacles. This system relies on a sensor-based approach, utilizing cost-effective alternatives to high-precision sensors. By compensating for the limitations of these alternatives, the control system maintains accuracy and reliability while keeping production costs manageable. Finally, the design emphasizes use-centric features to prioritize safety, reliability, and ease of use. These considerations ensure that the robot effectively meets the needs of its target audience, offering a practical and accessible solution to mobility challenges.

1.6 Impact to Individual, Society, and Nation

The robot's impact extends across individual, societal, and national levels, addressing critical challenges and fostering meaningful advancements. On an individual level, the robot significantly reduces physical strain and enhances independence for elderly individuals and those with mobility challenges. By providing an accessible and reliable tool for navigating stairs and carrying loads, it empowers users to maintain autonomy and improve their quality of life. At a societal level, the robot promotes inclusivity and fosters a more equitable environment. By addressing mobility-related challenges, it contributes to improving the overall quality of life for individuals with physical limitations. Accessible robotics of this kind serve as a powerful tool for bridging gaps in societal equality, ensuring that technological advancements benefit a broader range of people.

On a national scale, the robot strengthens local innovation in the field of robotics, contributing to technological progress and economic growth. By developing practical and impactful solutions to global challenges, the nation can position itself as a leader in the rapidly evolving robotics industry. This advancement not only boosts technological competitiveness but also highlights the nation's commitment to addressing societal needs through innovation. Furthermore, the robot's scalable and cost-effective design aligns with global sustainability goals. By promoting the development of affordable technology for societal benefit, the project underscores the importance of sustainable innovation. This approach ensures that technological progress supports broader societal goals, making it a valuable contribution to long-term development.

2. METHODOLOGY

2.1 Mechanical Configuration of Modified Rocker-Bogie Mechanism

The robot model is described in detail while analysing kinematic constraints to refine the design based on experimental results. Control parameters are established for sensitivity analysis to identify optimal design values. Key kinematic constraints include the maximum height and minimum step that the robot can ascend or descend.

2.2 Robot Design and Kinematics Constraints

The mobile robot's design comprises a chassis and six wheels individually controlled by actuators (see **Figure *1***). The front wheel w_1 and middle wheel w_2 are connected via a passive rotation joint denoted by a bogie and Link $_1$. This link forms a triangle shape defined by parameters L_1, L_2, and L_4.

- L_1 : Distance between the front wheel's center and the bogie's center.
- L_2 : Distance between the middle wheel's center and the bogie's center.
- L_4 : Distance between the front and middle wheels.

The rear wheel w_3 connects to the chassis, forming an imaginary link between its center and the bogie's center referred to as Link 2 with parameter L_3 . Additional parameters include:

- L_5 : Distance from the bogie to the center of mass.
- L_6 : Distance from the chassis to the ultrasonic sensor.

The only sensor installed is an ICM-20948 IMU sensor in the chassis for measuring rotation and velocity. Detailed dimensions and parameters are presented in **Table *1*** and **Figure *2*** shows the schematic diagram of the 2D model.

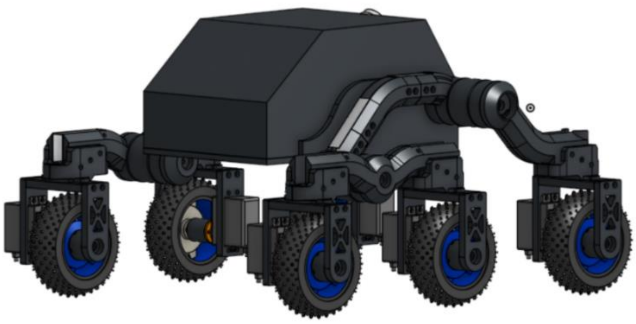


Figure 1. CAD model design of a wheeled robot.

Table 1. Parameters of the wheeled robot. Units in m, length (L), width (W), and height (H).

Specification	Design 1	Design 2	Design 3
Chassis Dimensions (L × W × H	266 ×168 × 60	300 × 192 × 50	221.7 x 156 x 106
Wheel Radius	Front (r_1): 32,.5	Front (r_1): 42.5	Front (r_1): 42.5
	Middle (r_2): 32.5	Middle (r_2): 42.5	Middle (r_2): 42.5
	Rear (r_3): 32.5	Rear (r_3): 42.5	Rear (r_3): 42.5
Lengths	l_1:	l_1: 143.7	l_1: 104.35
	l_2:	l_2: 143.7	l_2:1044.35
	l_3:	l_3: 330	l_3: 240
	l_4:	l_4: 220	l_4: 160

The kinematic constraints of the wheeled robot are analyzed based on these parameters. **Figure 2** shows the nine parameters of the robot, including the radius of the wheels and the center of mass. The following geometric relationships prevent collisions between links:

i. Parameters L_1, L_2, and L_4 must maintain a triangular shape for improved stability during stair navigation.

ii. The radius of wheels w_1, w_2,and w_3 must be smaller than parameters L_1, L_2, and L_3 respectively.

iii. The sum of radii $r_1 + r_2 > L_4$ must hold true to prevent collisions between front and middle wheels.

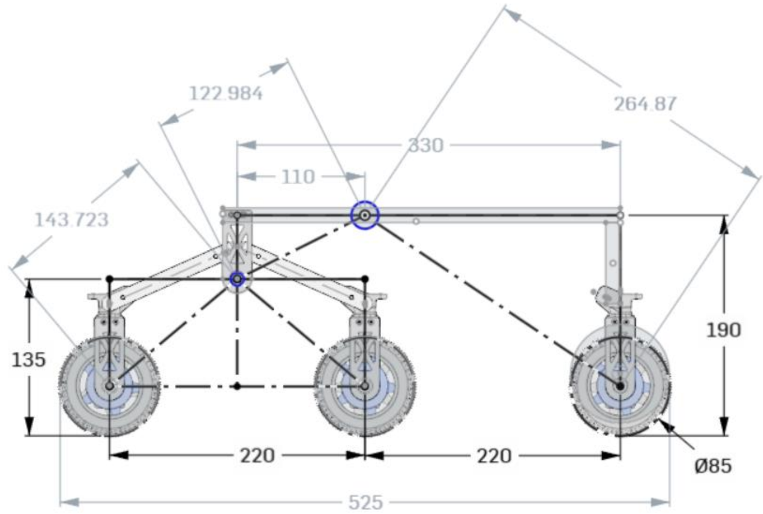


Figure 2. 2D schematic diagram of the wheeled robot of prototype 2.

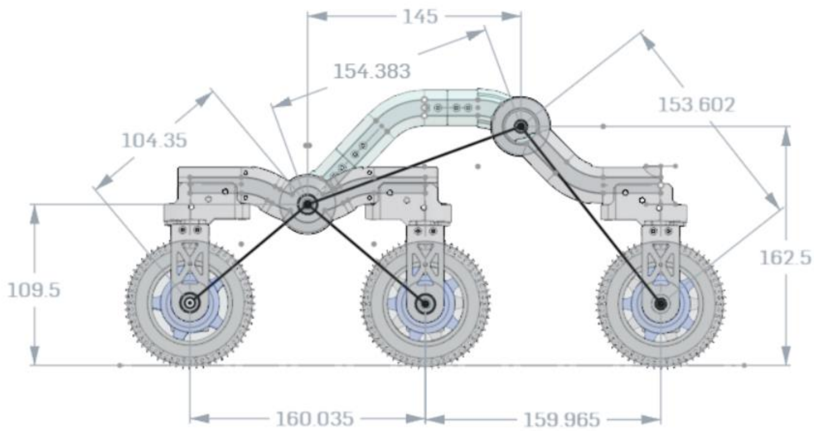


Figure 3. 2D schematic diagram of the wheeled robot of prototype 3.

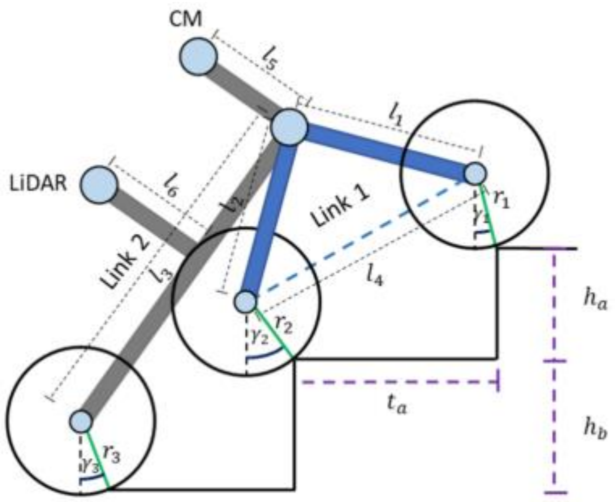


Figure 4. 2D Schematic diagram of the wheeled robot.

2.3 Robot Design Methodology

Designing a robot based solely on experience does not guarantee optimal performance results; multiple variables, objectives, constraints, and evaluation criteria must be considered. Key control parameters include link lengths and wheel radii—modifiable factors evaluated for robustness enhancement. If new design parameters comply with established kinematic constraints while minimizing trajectory slopes during navigation, they can be deemed optimal. The Korea Electronics Technology Institute (KETI) (Pico et al., 2022) developed the foundational six-wheeled mobile robot adapted in this study. Optimal parameter combinations were identified through minimizing center-of-mass trajectory slopes during stair navigation, shown in **Table 2**.

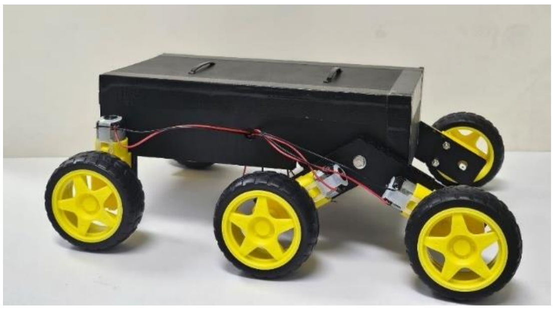
Table 2. Optimal design results of the wheeled robot.

Control factors (mm)	L_1	L_2	L_3	r_1	r_2	r_3
Optimal	104.35	104.35	240	42.5	42.5	42.5

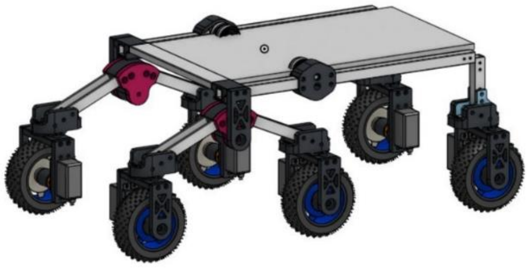
3. RESULTS AND DISCUSSION

3.1 Design improvement on the Rocker-Bogie Robot

The iterative design process significantly enhanced stair navigation capabilities. The initial design (**Figure 5**a), characterized by a distance of 24.2 cm between front and rear wheels with insufficient motor torque due to limited motor driver configurations (one driver controlling six motors), failed at both step types (6x30 cm and 8x34 cm). In contrast, the second iteration (**Figure 5**b) increased wheel diameter to 85 mm while restructuring based on average Malaysian stair heights. This version utilized three motor drivers controlling two motors each for better torque management but remained too heavy for effective operation. The optimum design (**Figure 5**c) addressed prior issues by further increasing distances between wheels while adjusting pivot distances, enabling successful navigation of both step types.



(a) Initial design



(b) Second design

(c) Optimum design

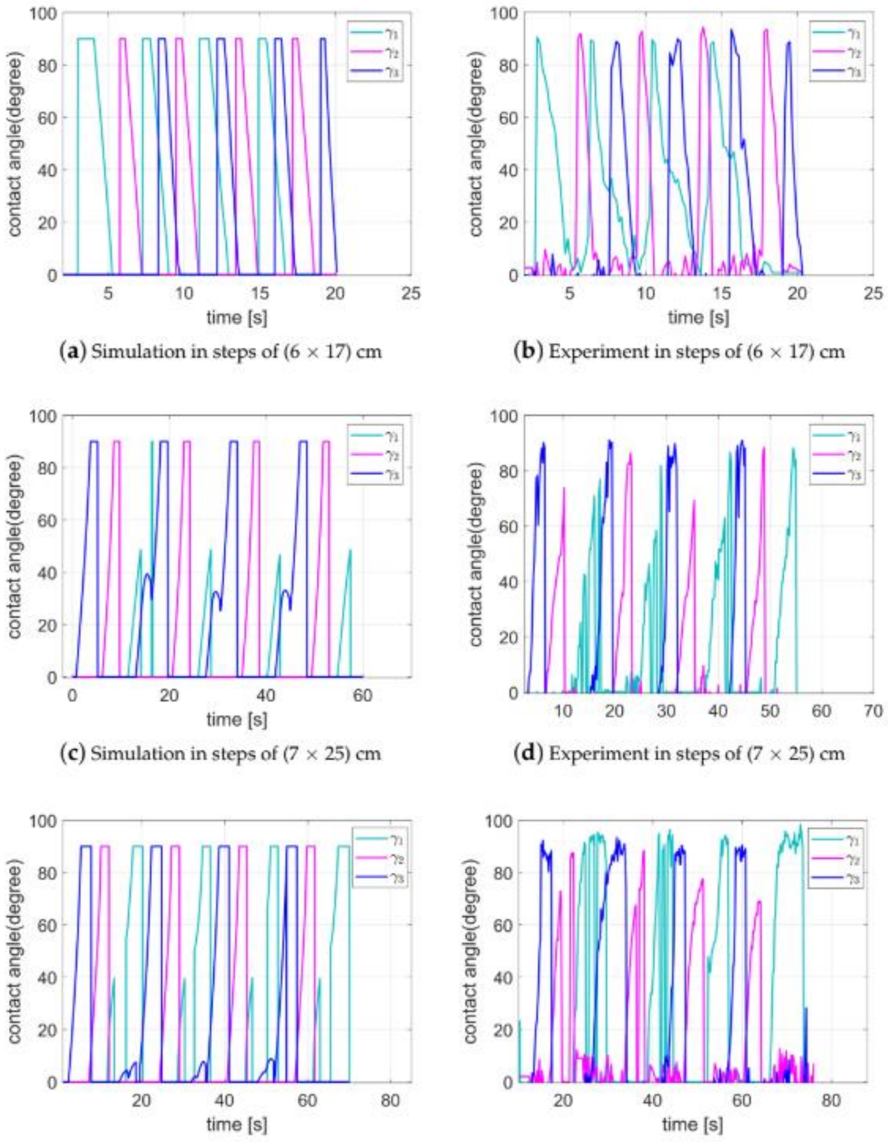
(d) Experiment on steps of (6×30) cm

(e) Experiment on steps of (8 × 34) cm

Figure 5. Experiment while climbing up and down stairs. (a) initial design; (b) second design; (c) optimum design; (d) climbing up and down on steps of (6 × 30) cm; (e) climbing up and down on steps of (8 × 34) cm.

3.2 Result of Rocker-Bogie Robot Design

This research examines the contact angle measurements between the robot's wheels and the ground during experiments involving steps of varying dimensions. The data aligns with the expected performance of the robot's front and middle wheels but shows deviations for the rear wheel. The contact angles were measured using an IMU sensor (ICM-20948). In the experiment involving steps measuring 6 × 30 cm, the contact angles for the front wheel (blue) and the middle wheel (orange) are depicted in **Figure** ***6***a. Consistent with the expected behavior, the contact angle approached approximately 90° at the edge of each step and returned to 0° on flat surfaces. This fluctuating behavior was observed as the robot navigated the ascent and descent of the steps. Similarly, during experiments with larger steps of 8 × 34 cm (**Figure** ***6***b), the contact angles followed a comparable pattern. The front and middle wheels reached a contact angle of 90° at the step edges before transitioning to 0° on flat ground, replicating the dynamics noted earlier.



(**a**) Simulation in steps of (6 × 17) cm

(**b**) Experiment in steps of (6 × 17) cm

(**c**) Simulation in steps of (7 × 25) cm

(**d**) Experiment in steps of (7 × 25) cm

(**e**) Simulation in steps of (11 × 27) cm

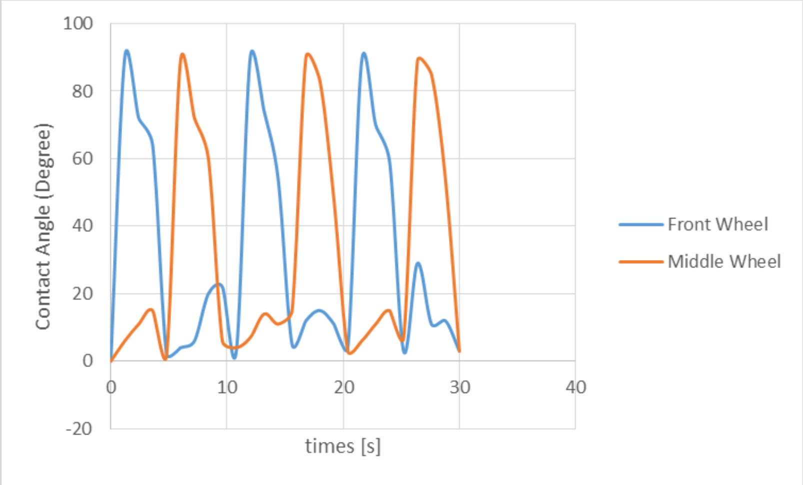
(**f**) Experiment in steps of (11 × 27) cm

Figure 6. Contact angle measurement detection between wheel–ground.

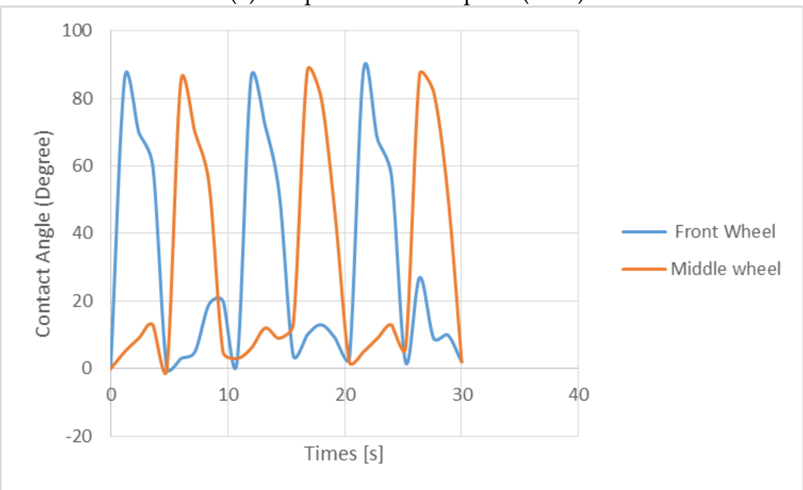
A notable difference between this study and the referenced research lies in the activation of the emergency controller. The referenced study included an emergency control system that activated when the front wheel lost ground contact during the descent of 11 × 27 cm steps. This feature was absent in the current robot design. As a result, this study focuses solely on the contact angle data for the front and middle wheels, tailoring the discussion to the initial scope of analysis. The objective of this study was to identify optimal design parameters for a six-wheeled robot capable of navigating stairs while adhering to kinematic constraints. Through an iterative design process, the goal was to achieve a balance between motor torque, wheel size, and the geometry of the rocker-bogie mechanism, ultimately enhancing the robot's stability and adaptability for service applications. The findings reveal that design modifications significantly improved the robot's ability to navigate steps of varying dimensions, specifically 6 × 30 cm and 8 × 34 cm.

The design process underwent three key iterations. The first iteration faced major challenges due to insufficient motor torque and an inefficient motor control system. A single motor driver controlled six motors, resulting in poor torque distribution and limited responsiveness. The robot failed to ascend steps, highlighting the need to optimize motor control and torque. Improvements in the second iteration included increasing the tire diameter to 8.5 cm, restructuring the body to accommodate average stair heights, and using three motor drivers to independently control two motors each. These modifications enhanced torque distribution and climbing ability but revealed a weight issue that constrained motor effectiveness. The robot was able to ascend smaller 6 × 30 cm steps but struggled with larger dimensions, necessitating further optimization.

Key changes in the final iteration included reducing the distance between the front and rear wheels to 32 cm and adjusting the bogie-to-rocker pivot distance to 14.5 cm. These adjustments significantly improved the robot's performance, allowing it to navigate both 6 × 30 cm and 8 × 34 cm steps efficiently. This iteration emphasized the importance of optimizing wheel placement, pivot geometry, and suspension systems to enhance overall stability and adaptability.



(a) Experiment in steps of (6x30) cm



(b) Experiment in steps of (8x34) cm

Figure 7. Contact angle measurement between wheel–ground: (a) Experiment in steps of (6 x 30) cm; (b) Experiment in steps of (8 x 34) cm.

From a kinematic perspective, the robot's stability during ascent and descent is influenced by the interplay of wheel diameter, placement, and rocker-bogie geometry. Adjustments in these parameters redistributed the center of mass, enabling more efficient force application during movement. Contact angle measurements confirmed these improvements, with the front and middle wheels displaying expected behavior. However, the rear wheel's inconsistent contact angle indicates the need for further refinement in its design and positioning.

To further enhance the robot's stability and adaptability, several recommendations are proposed. Redesigning the rear wheel and its placement could improve ground contact consistency and stability. Exploring more powerful motors or implementing a variable motor control system could enable the robot to handle larger loads and steeper steps. Utilizing lightweight yet durable materials could reduce strain on the motors, improving performance and adaptability to uneven terrains. Additionally, refining the rocker-bogie suspension system could improve shock absorption and adaptability to varied surfaces, ensuring optimal ground contact at all times.

5. CONCLUSION

This study successfully developed and refined a six-wheeled rocker-bogie robot capable of overcoming one of the toughest challenges in robotics: climbing stairs. Stairs, with their varying dimensions and materials, present significant obstacles, particularly in indoor and outdoor environments. The aim was to design a versatile and reliable robot for practical applications such as delivery, healthcare, and maintenance. Through iterative design improvements, the robot progressed from being unable to climb basic stairs to reliably navigating steps of 6 × 30 cm and 8 × 34 cm. Key optimizations included increasing wheel size, enhancing motor control, and refining the suspension system. These adjustments resulted in a design that balanced stability, adaptability, and functionality.

While some challenges remain—particularly with the rear wheel losing contact during certain movements—the findings provide a strong foundation for future enhancements. Potential improvements include refining the rear wheel design, integrating advanced sensing systems, and improving energy efficiency. This study demonstrates the potential of robotics to address real-world challenges and lays the groundwork for further innovations in stair-climbing robots. By continuing to refine design parameters and integrating advanced technologies, the future of service robotics promises even greater versatility and impact, ultimately improving the way we live and work.

Acknowledgements: The authors thank Universiti Malaysia Sabah (UMS) for providing a grant under No. DKP0173. "Sakinah binti Muhamad Hisham" is the recipient of the Universiti Malaysia Pahang (UMP) Post-Doctoral Fellowship in Research. The authors also want to express their deepest gratitude to their lecturer, Dr. Mohd Kamal bin Kamarulzaman, for his invaluable guidance, insightful feedback, and unwavering support throughout the KM30903 Mechanical Design I course. His expertise and encouragement have been instrumental in shaping our work and ensuring its completion. The help from the group members – Derry Dexler Sylvester, Aiman bin Idris, Noor Dian Eka Wahyu binti Mohamad, Nurhafiza binti Lokman, and Nur Nabila Syafiqah binti Sufian, for their dedication, hard work, and collaboration during this project. Their collective efforts, from brainstorming and research to practical implementation, have significantly contributed to the quality of this study and made the journey both productive and memorable. Finally, the authors extend their heartfelt thanks to everyone who has supported and motivated us throughout this process, providing the foundation for this academic accomplishment.

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