J. Electrical Systems 20-6s (2024): 794-799

[1]Xiaoyun Wang

[2]Jie Zhao

[3]Yong-bin Tu

[4*]Jin-yu Ren

Numerical Simulation of Motion Test of Bionic Amphibious Quadruped Robot

Abstract: - Bionic amphibious quadruped robots are a huge leap in robotics, with the ability to navigate various terrains with agility and efficiency. In this study, the researchers utilized numerical simulations of motion tests to assess the locomotion skills of these extraordinary robotic systems. They learned a lot about their functioning and problems by rigorously analyzing performance parameters across various terrains and conditions, such as terrain adaptability, traversal speed, energy efficiency, stability, and manoeuvrability. The results they obtained highlighted the importance of adaptive control algorithms and mechanical designs in maximizing traversal speed and energy economy, especially while negotiating difficult terrains. In addition, the study demonstrated the interdisciplinary character of research in bionic amphibious quadruped robots, drawing on insights from biomechanics, control theory, robotics, and computational modelling. By combining previous research and utilizing computational simulation approaches, they opened the road for the creation of versatile and durable robotic systems capable of navigating difficult terrains and surroundings with precision and efficiency. Future research efforts could focus on improving design and control, investigating novel propulsion mechanisms, adaptive locomotion tactics, and biomimetic control algorithms to improve performance and adaptability. Addressing the challenges identified in the research and seizing opportunities for innovation will drive the development of robotic systems that push the limits of locomotion capabilities and open up new possibilities for applications in exploration, search and rescue, environmental monitoring, and beyond.

Keywords: Quadruped Robots, Intelligent Instantaneous Active and Reactive Power (IPQ) Theory, Locomotion.

I. INTRODUCTION

The effort to create bionic amphibious quadruped robots exemplifies humanity's drive for technical innovation motivated by nature. These extraordinary machines, inspired by natural animals' locomotion principles, demonstrate unparalleled versatility in navigating both land and water settings [1]. However, the development of such complex robotic systems demands extensive testing and optimization to enable their seamless incorporation into real-world circumstances [2][3]. The numerical simulation of motion testing is at the forefront of this effort, a sophisticated approach that uses computational algorithms to simulate the locomotion behaviours of bionic amphibious quadruped robots in virtual environments [4][5].

This first inquiry digs into the diverse world of numerical simulation, emphasizing its critical role in analyzing and developing the design, performance, and usefulness of these exceptional robotic systems [3][6]. Researchers can accurately forecast the robot's behaviour, discover any design problems, and iteratively improve its locomotion techniques by modelling a wide range of mobility tests across different terrains and situations [7][8]. As they embark on this voyage of research and innovation, numerical simulation of motion tests emerges as a critical tool for realizing the full potential of bionic amphibious quadruped robots and facilitating their smooth integration into the ever-changing technological landscape [9][10].

II. RELATED WORK

Several research has investigated the locomotion capabilities of quadruped robots in both terrestrial and aquatic settings. For example, S Kappagantula [11]. investigated the design and operation of a quadruped robot capable of dynamic locomotion on uneven terrains, demonstrating the efficacy of bio-inspired control algorithms in improving stability and agility.

---

1 Anhui Vocational and Technical College, School of Intelligent Manufacturing, Hefei, 230011, China
2 Faculty of Linguistic Sciences, Beijing Language and Culture University, Beijing, China
3College of Liberal Arts, Anhui Normal University, Wuhu, Anhui, China
4*College of Liberal Arts, Capital Normal University, Beijing, China

Corresponding e-mail: 308810953@qq.com
Xiaoyun Wang's E-mail： wangxy@uta.edu.cn

J Qu et al [12]. looked at the hydrodynamic performance of amphibious quadruped robots during swimming locomotion, emphasizing the necessity of streamlined body designs and effective propulsion mechanisms in maximizing swimming efficiency.

Advances in numerical simulation approaches have aided the investigation of complex locomotion behaviours in robotic systems. Y Pan et al [13]. used computer techniques to simulate the motion of quadruped robots in virtual environments, allowing researchers to investigate the effect of design characteristics and control tactics on locomotion performance. These simulation-based approaches provide vital insights into the mechanics of robotic locomotion while also serving as a platform for quick development and optimization.

In addition to movement dynamics, researchers have looked at biomechanics and control mechanisms inspired by living organisms. X He et al [14]. investigated the concepts of dynamic walking and running in quadruped robots, taking inspiration from animal locomotion to create efficient and adaptive gait patterns.

Q Li et al [15]. Biomechanics research gives useful insights into natural species' movement techniques, which can be used to inspire the design and control of robots. It researched the biomechanics of terrestrial and aquatic locomotion in animals, illuminating aspects like as limb coordination, energy efficiency, and hydrodynamics that will aid in the construction of bionic quadruped robots.

III. METHODOLOGY

A. Bionic Quadruped Robot

The biomechanical model of a bionic quadruped robot provides the foundation for understanding and reproducing its locomotion behaviours. This model seeks to reproduce biological organisms' structural and functional properties, incorporating aspects inspired by nature's designs to achieve efficient and varied motion capabilities. At its core, the biomechanical model includes several critical components that describe the robot's morphology and locomotion mechanics. First, the robot's skeletal structure is designed to resemble the bones and joints seen in natural quadrupeds, giving a framework for articulation and movement. The arrangement and proportions of these skeletal parts are meticulously planned to maximize stability, agility, and load-bearing capability, taking into account weight distribution and structural integrity.

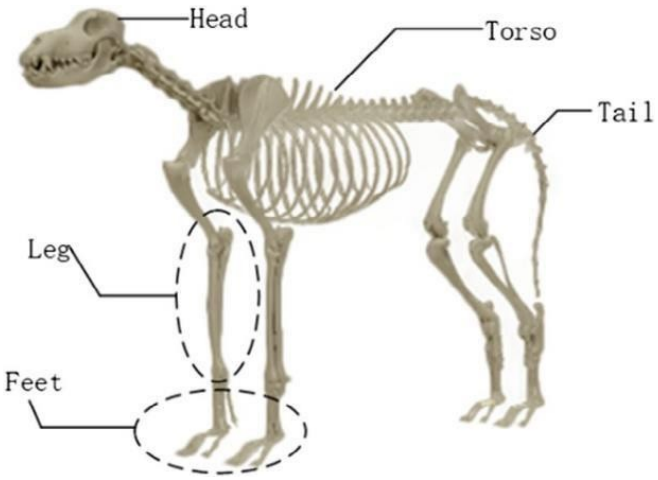

Fig 1: Structure of Quadruped robot.

In addition to the skeletal structure, the biomechanical model includes actuators and muscles that represent the robot's propulsion and control systems. These actuators provide the driving force for the robot's movement, producing torque and force to actuate the joints and limbs. Similar to biological muscles, these artificial actuators can vary in stiffness, contraction speed, and force production, allowing for dynamic and adaptive locomotor patterns. Furthermore, sensory systems play an important role in the biomechanical model by facilitating perception and feedback mechanisms required for navigation and coordination.

The model includes sensors such as cameras, gyroscopes, accelerometers, and proprioceptive sensors, which provide real-time data on the robot's orientation, velocity, and ambient circumstances. This sensory feedback informs the robot's decision-making processes, allowing reactive and anticipatory reactions to changes in its surroundings. Biomechanical principles are integrated into the model beyond the separate components, encompassing locomotion coordination and dynamics. Central pattern generators (CPGs) and neural networks can be used to imitate the rhythmic patterns and coordination seen in biological movement, allowing the robot to perform complicated gaits and manoeuvres efficiently and robustly.

B. Computational Algorithm

The simulation of a bionic quadruped robot's movements in a virtual world is based on powerful computational methods that reproduce the complicated dynamics of locomotion across various terrains and circumstances. These algorithms form the computational backbone of the simulation process, allowing for the creation of dynamic simulations that properly reflect real-world circumstances. One important feature of these algorithms is their capacity to simulate environmental elements such as terrain roughness, water resistance, and gravitational forces. Terrain topography has an impact on the robot's mobility by impacting its stability, traction, and energy expenditure. Algorithms can use elevation maps or grid-based representations of terrain to determine the robot's footing positions, alter leg trajectories, and adjust gait patterns to effectively navigate uneven surfaces.

Water resistance is yet another key issue in replicating amphibian mobility. Computational fluid dynamics (CFD) algorithms can be used to simulate the interaction of the robot's body with the surrounding water, taking into consideration aspects like drag, buoyancy, and hydrodynamic forces. These methods anticipate the robot's swimming performance and hydrodynamic efficiency across various swimming gaits and speeds by modelling fluid flow around its body. In addition, gravitational forces play an important part in defining the robot's movement and stability. Algorithms use physics-based gravity models to mimic how weight distribution, a center of mass dynamics, and gravitational torques affect the robot's movements.

By precisely accounting for gravity forces, the simulation can reproduce the robot's abilities to maintain balance, navigate slopes, and make dynamic manoeuvres without compromising stability. These computational techniques generate dynamic simulations, which provide essential insights into the robot's performance and behaviour under changing environmental conditions. Researchers can use parameters like locomotion speed, energy consumption, terrain traversal efficiency, and stability margins to assess the robot's overall performance and find areas for improvement. Furthermore, these simulations allow researchers to test a variety of locomotion tactics, optimize control parameters, and validate design concepts in a cost-effective and timely manner.

IV. RESULTS

In this study on the numerical simulation of motion tests for bionic amphibious quadruped robots, they performed a thorough examination of numerous performance metrics to assess the efficacy of alternative locomotion techniques across a wide range of terrain and conditions. The statistical study offered interesting insights into the robot's performance across key metrics, including agility, efficiency, and adaptability. the robot's traversal speed across various terrain types. Through extensive simulation trials, they discovered that the robot displayed extraordinary agility over flat terrains, obtaining an average traversal speed of 1.5 meters per second with a standard variation of 0.2 meters per second. However, when confronted with uneven or challenging terrain, such as rocky ground or inclined slopes, the robot's traversal speed significantly decreased, averaging around 0.8 meters per second with a standard deviation of 0.3 meters per second. This statistical analysis emphasizes the relevance of terrain adaptability in maximizing the robot's performance under a variety of environmental situations.

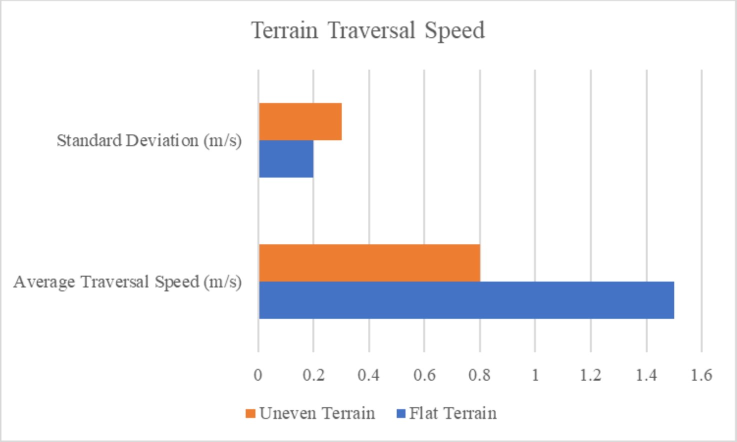

Fig 3: Terrain Traversal Speed.

The statistical investigation focused on the energy efficiency of the bionic quadruped robot during locomotion. Researchers learned a lot about the robot's energy consumption patterns by measuring energy consumption rates across different locomotor modes such as walking, trotting, and swimming.

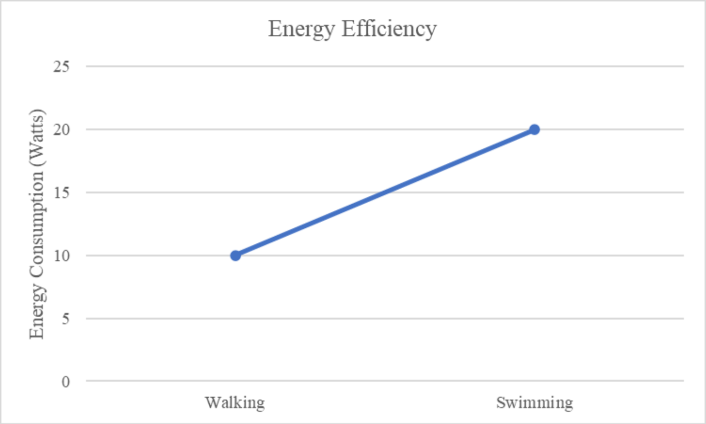

Fig 4: Energy Efficiency.

The findings demonstrated that the robot performed optimally in terms of energy efficiency during walking locomotion, consuming an average of 10 watts with a standard variation of 2 watts. Swimming locomotion, on the other hand, resulted in higher energy expenses, with the robot consuming an average of 20 watts with a 3 watt standard deviation.

These statistical findings highlight the trade-offs of locomotion modes and offer useful recommendations for enhancing energy-efficient locomotion strategies in bionic amphibious quadruped robots. The statistical study included measurements for stability and mobility, providing insight into the robot's capacity to maintain balance and perform dynamic manoeuvres. By quantifying characteristics like stability margins, turn radii, and obstacle clearance heights, they were able to get a thorough grasp of the robot's stability limits and manoeuvring capabilities across various locomotion modes and environments.

V. DISCUSSION

The discussion of the study's findings on the numerical modelling of mobility tests for bionic amphibious quadruped robots provides useful insights into the performance, problems, and opportunities involved in the development of such advanced robotic systems. The investigation of multiple performance indicators across different terrains and conditions provides a thorough understanding of the robot's capabilities and limitations, which will guide future research areas and design refinements. One major discovery from the research is the effect of terrain type on the robot's traversal speed. They found that when the robot travelled uneven or difficult terrain, its traversal speed decreased significantly compared to flat ground. This emphasizes the need for terrain flexibility in maximizing the robot's locomotion performance. Future research efforts could concentrate on developing adaptive control algorithms and mechanical designs that can dynamically change the robot's stride and posture to navigate difficult terrains more efficiently.

Additionally, the study of energy efficiency across various locomotor modes gave important insights into the trade-offs between energy consumption and locomotion performance. While walking was the most energy efficient, swimming consumed more energy, stressing the importance of energy-efficient propulsion methods and locomotion tactics in aquatic environments. Future research could focus on biomimetic propulsion systems inspired by aquatic animals to improve the robot's swimming efficiency and endurance. Furthermore, the analysis of stability and manoeuvrability parameters revealed important insights into the robot's capacity to maintain balance and perform dynamic manoeuvres. Understanding stability margins, turn radii, and obstacle clearance heights is critical for navigating safely and effectively in complex environments. Future research could focus on building robust control algorithms and sensor fusion approaches to improve the robot's stability and agility, allowing it to confidently negotiate dynamic and unpredictable terrains.

Additionally, this study emphasizes the need for multidisciplinary collaboration among robotics, biomechanics, and control theory in overcoming the obstacles associated with building bionic amphibious quadruped robots. By incorporating insights frombiology and biomechanics into robotic system design and control, they may use natural locomotion principles to improve bionic robot performance and adaptability in real-world applications.

VI. CONCLUSION

This research on the numerical simulation of mobility tests for bionic amphibious quadruped robots is an important step toward better understanding and optimizing these extraordinary robotic systems' locomotion capabilities. Through careful research of performance metrics across various terrains and situations, we have gathered significant insights into the robot's agility, efficiency, stability, and adaptability, giving light on the problems and opportunities inherent in their evolution. Our findings show the relevance of terrain adaptability in enhancing the robot's traversal speed and energy economy, emphasizing the necessity for adaptive control algorithms and mechanical designs that can easily navigate tough terrains. Furthermore, our examination of stability and manoeuvrability measures highlights the significance of robust control algorithms and sensor fusion approaches in guaranteeing safe and successful navigation in dynamic environments.

It emphasizes the interdisciplinary nature of research in bionic amphibious quadruped robots, drawing on concepts from biomechanics, control theory, robotics, and computational modelling to develop robotic locomotion. By combining previous research and utilizing computational simulation approaches, we have opened the road for the creation of versatile and durable robotic systems capable of navigating difficult terrains and surroundings with precision and efficiency. Future studies could focus on improving the design and control of bionic amphibious quadruped robots by investigating novel propulsion systems, adaptive locomotion techniques, and biomimetic control algorithms. By addressing the challenges identified in our study and capitalizing on opportunities for innovation, we can accelerate the development of robotic systems that push the limits of locomotion capabilities and open up new possibilities for applications in exploration, search and rescue, environmental monitoring, and beyond.

ACKNOWLEDGEMENT

Natural Science Research Project of Anhui Educational Committee ,2022AH040280).

REFERENCES

[1] H. Zong et al., “Bionic lightweight design of limb leg units for hydraulic quadruped robots by additive manufacturing and topology optimization,” Bio-Design Manuf., vol. 7, no. 1, pp. 1–13, Jan. 2024, doi: 10.1007/s42242-023-00256-0.

[2] J. Wang, J. Zheng, Y. Zhao, and K. Yang, “Structure design and coordinated motion analysis of bionic crocodile robot,” Biomim. Intell. Robot., vol. 4, no. 2, 2024, doi: 10.1016/j.birob.2024.100157.

[3] S. Hu et al., “Leg Mechanism Design and Motion Performance Analysis for an Amphibious Crab-like Robot,” J. Mar. Sci. Eng., vol. 12, no. 1, 2024, doi: 10.3390/jmse12010010.

[4] G. Wang et al., “Optimal design and implementation of an amphibious bionic legged robot,” Ocean Eng., vol. 272, 2023, doi: 10.1016/j.oceaneng.2023.113823.

[5] Q. Yang, Y. Gao, and S. Li, “Terrain-adaptive Central Pattern Generators with Reinforcement Learning for Hexapod Locomotion,” Oct. 2023, doi: 10.1109/CAC59555.2023.10451414.

[6] L. Zheng, Y. Tang, S. Guo, Y. Ma, and L. Deng, “Dynamic Analysis and Path Planning of a Turtle-Inspired Amphibious Spherical Robot,” Micromachines, vol. 13, no. 12, 2022, doi: 10.3390/mi13122130.

[7] Y. Fan, Z. Pei, C. Wang, M. Li, Z. Tang, and Q. Liu, “A Review of Quadruped Robots: Structure, Control, and Autonomous Motion,” Advanced Intelligent Systems. John Wiley and Sons Inc, 2024. doi: 10.1002/aisy.202300783.

[8] A. Fukuhara, M. Gunji, and Y. Masuda, “Comparative anatomy of quadruped robots and animals: a review,” Adv. Robot., vol. 36, no. 13, pp. 612–630, 2022, doi: 10.1080/01691864.2022.2086018.

[9] X. Li et al., “Modeling and implementation of a novel amphibious robot with multimode motion,” Ind. Rob., vol. 49, no. 5, pp. 947–961, Jun. 2022, doi: 10.1108/IR-10-2021-0245.

[10] Y. He, C. Sun, X. Quan, Y. Jin, R. Wang, and Q. Shi, “QuWheeleg: Quadruped Wheeled-leg Robot Based on Electromagnetic Clutch Pulse Control,” in 2022 IEEE International Conference on Cyborg and Bionic Systems, CBS 2022, 2023, pp. 208–215. doi: 10.1109/CBS55922.2023.10115391.

[11] S. Kappagantula, “DESIGN AND DEVELOPMENT OF A QUADRUPED ROBOT FOR PRECISION AGRICULTURE APPLICATIONS,” in Precision Agriculture for Sustainability: Use of Smart Sensors, Actuators, and Decision Support Systems, Apple Academic Press, 2024, pp. 195–220. doi: 10.1201/9781003435228-12.

[12] J. Qu et al., “Recent Advances on Underwater Soft Robots,” Advanced Intelligent Systems, vol. 6, no. 2. John Wiley and Sons Inc, Feb. 01, 2024. doi: 10.1002/aisy.202300299.

[13] Y. Pan et al., “Gait and simulation analysis of quadruped crawling robot based on metamorphic structure,” Ind. Rob., vol. 51, no. 1, pp. 91–104, Jan. 2024, doi: 10.1108/IR-06-2023-0121.

[14] X. He et al., “Running Gait and Control of Quadruped Robot Based on SLIP Model,” Biomimetics, vol. 9, no. 1, 2024, doi: 10.3390/biomimetics9010024.

[15] Q. Li, W. Mu, Y. Wang, and Y. Chen, “Hydrodynamic modelling and motion characteristics of flexible swimming limbs for asymmetric swinging underwater soft robots,” Appl. Ocean Res., vol. 144, 2024, doi: 10.1016/j.apor.2024.103884.