Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 2 (2024)

Piezoelectric Sensing for Seamless Motion in Mobile Robotics

Dr. M. Ravi, Mr. P. Saran, Mr. V. Vaidheeswaran, Mr. M. Veeraragavan

Professor, Department of Mechatronics, K. S. Rangasamy College of Technology, Tiruchengode – 637215, Tamil Nadu, India.

UG Student, Department of Mechatronics, K. S. Rangasamy College of Technology, Tiruchengode – 637215, Tamil Nadu, India.
UG Student, Department of Mechatronics, K. S. Rangasamy College of Technology, Tiruchengode – 637215, Tamil Nadu, India.
UG Student, Department of Mechatronics, K. S. Rangasamy College of Technology, Tiruchengode – 637215, Tamil Nadu, India.

Abstract:- Piezoelectric materials are important in mobile robotics, service sensing, actuation, energy harvesting, and vibration control applications. This paper introduces a sophisticated framework for piezoelectric based motion design for mesoscale mobile robots. Utilizing a custom-designed mechanism, it amplifies piezoelectric forces and transmits them through a sliding mechanism to extend the flow rate of the material. Unlike traditional sliding and planting methods, this design eliminates the idea of crashing and expands the robot's ability to cover terrain. Our paper includes motion strategies, kinematic modelling, mechanical optimization, and control strategies for mesoscale robots, providing details on their development and potential applications in mobile robotics. Also, piezoelectric energy harvesting devices provide the ability to remove ambient energy from vibration and mechanical deformation, increasing mobile robot autonomy and durability, and they can be used in vibration control systems to dampen oscillations and unwanted vibration. The integration of materials holds great promise to improve the capability, efficiency, and autonomy of robotic systems in applications ranging from detection and monitoring to healthcare.

Keywords*: Piezoelectric, Oscillation Mechanism, Micro- robotics, Robots, Navigation System.*

1. Introduction

The intersection of robotics and advanced materials has spurred innovative developments in the field of mobile robotics. Among these, piezoelectric materials have emerged as promising candidates for creating efficient and versatile robotic systems. This introduction provides a glimpse into the realm of piezoelectric mobile robots, highlighting their significance and the objectives of the research at hand. Piezo- electricity, a phenomenon where certain materials generate electric charges in response to mechanical stress, has garnered attention for its application in robotics. By harnessing this property, researchers have explored the creation of mobile robots capable of intricate movements and energy-efficient operation.

One notable design paradigm involves the utilization of curved tail oscillation, a mechanism inspired by natural locomotion, to propel these robots forward with remarkable agility and control. The development of piezoelectric mobile robots holds immense significance across various domains. In sectors such as search and rescue, exploration, and environ- mental monitoring, these robots offer unparalleled manoeuvrability in complex and constrained environments. Moreover, their potential extends to microscale applications, where conventional propulsion methods face limitations. By delving into the intricacies of curved tail oscillation in piezoelectric robots, this research aims to unlock new possibilities for enhancing mobility, energy efficiency, and adaptability in robotic systems.

The primary objective of this study is to investigate the efficacy of curved tail oscillation as a propulsion mechanism in piezo- electric mobile robots. Through a combination of theoretical analysis, computational modelling, and experimental validation, the study seeks to elucidate the underlying principles governing the interaction between piezoelectric actuators and the robot's tail structure. By elucidating these dynamics, the research endeavours to optimize the design parameters and control strategies for achieving superior performance in terms of speed, manoeuvrability, and energy efficiency. Ultimately, the insights gained from this study aim to advance the state- of-the-art in piezoelectric robotics and pave the way for novel applications in diverse real-world scenarios.

2. Background of the Invention

Piezoelectric materials have garnered significant attention in robotics due to their unique ability to convert mechanical energy into electrical energy and vice versa. This property makes them particularly attractive for developing innovative robotic systems that can harness ambient mechanical vibrations or deformations for locomotion and energy harvesting. In recent years, there has been a growing interest in exploring the potential of piezoelectric actuators in creating mobile robots with enhanced agility, energy efficiency, and adaptability to various environments. Previous research in the field of piezoelectric robotics has demonstrated promising results, showcasing the feasibility of utilizing piezoelectric materials for propulsion, sensing, and manipulation tasks in robotic systems. Studies have investigated different configurations and control strategies to optimize the performance of piezoelectric actuators in various applications, ranging from micro robotics to soft robotics and beyond. Additionally, researchers have explored novel designs and mechanisms, such as curved tail oscillation, to leverage the unique characteristics of piezoelectric materials for locomotion in confined spaces or challenging terrains.

Key concepts and theories underpinning the development of piezoelectric mobile robots include the principles of piezoelectricity, mechanical resonance, and dynamic modelling of piezoelectric systems. Understanding the fundamental properties of piezoelectric materials, such as their electromechanical coupling coefficients, frequency response, and energy harvesting capabilities, is essential for designing efficient and robust robotic systems. Moreover, concepts from control theory, such as feedback control algorithms and motion planning techniques, play a crucial role in orchestrating the motion and behaviour of piezoelectric robots in real-world scenarios. By integrating insights from previous research and leveraging key concepts and theories, this study aims to explore the feasibility and performance of a thin piezoelectric mobile robot utilizing curved tail oscillation for locomotion. Through experimental validation and theoretical analysis, this research seeks to advance our understanding of piezoelectric robotics and contribute to the development of agile and energy- efficient robotic systems for various applications, including search and rescue, environmental monitoring, and exploration in challenging terrains.

3. Objectives

The primary aim of this invention is to augment the mobility capabilities of robotic systems, particularly in environments where conventional wheeled or tracked mechanisms may be limited. By leveraging the principles of piezoelectricity and curved tail oscillation, the invention seeks to enable robots to navigate diverse terrains with increased efficiency and adaptability. Another crucial objective is to improve the energy efficiency of mobile robotic platforms. Through the utilization of piezoelectric materials, which can convert mechanical strain into electrical energy, the invention aims to harness ambient mechanical vibrations or deliberate oscillations to power locomotion and other functionalities.

This emphasis on energy harvesting and utilization aligns with sustainability goals and extends operational endurance. The invention endeavours to facilitate agile manoeuvrability in robotic systems, enabling them to traverse complex landscapes with agility and precision. By integrating a curved tail oscillation mechanism inspired by natural locomotion principles observed in certain organisms, the invention seeks to enhance the robot's ability to navigate tight spaces, negotiate obstacles, and maintain stability during locomotion. Robotic systems often operate in harsh and unpredictable environments, where reliability and robustness are paramount. Therefore, a key objective of this invention is to enhance the robustness and reliability of mobile robots, ensuring consistent performance across various conditions and scenarios. By employing durable materials and innovative design principles, the invention aims to mitigate mechanical failures and enhance overall system resilience.

The invention aspires to promote versatility and adaptability in robotic applications, enabling them to fulfil diverse tasks and missions. Whether deployed in search and rescue operations, exploration missions, or industrial settings, the invention seeks to provide a flexible platform that can be tailored to specific requirements and environments. This versatility enhances the applicability and value proposition of the invention across different domains.

4. Summary of the Invention

Our invention introduces a groundbreaking approach to mobile robotics through the integration of thin piezoelectric materials and a unique curved tail oscillation mechanism. Unlike traditional bulky robotic designs, our invention focuses on maximizing mobility and efficiency while minimizing size and weight. The thin piezoelectric mobile robot capitalizes on the remarkable properties of piezoelectric materials, which generate electrical charge in response to mechanical stress. By strategically embedding these materials within the robot's structure, we enable precise control over its movements with minimal power consumption. Central to our innovation is the curved tail oscillation mechanism, inspired by nature's efficient locomotion strategies. This mechanism facilitates smooth and agile navigation through various terrains, allowing the robot to adapt to dynamic environments with ease.

The curvature of the tail enhances stability and manoeuvrability, enabling the robot to execute intricate motions with remarkable precision. Through extensive testing and refinement, we have demonstrated the capabilities of our invention in real-world scenarios, showcasing its versatility and reliability across a range of applications. From search and rescue missions in hazardous environments to surveillance and monitoring tasks in urban landscapes, the thin piezoelectric mobile robot offers unparalleled performance and adaptability.

5. Detailed Description of the Invention

The Piezoelectric Mobile Robot represents a groundbreaking advancement in the field of robotics, introducing a novel approach to locomotion that capitalizes on the unique properties of thin piezoelectric materials. At its essence, this revolutionary robot is designed to be compact, lightweight, and highly efficient, making it ideally suited for a wide range of applications where traditional power sources may be impractical or inaccessible. Piezoelectric materials, renowned for their ability to convert mechanical energy into electrical energy and vice versa, serve as the cornerstone of this innovative robot.

These materials exhibit a remarkable property known as the piezoelectric effect, whereby they generate an electric charge in response to mechanical stress or deformation. Conversely, when subjected to an electric field, they undergo mechanical deformation, resulting in movement or vibration. In the context of the Piezoelectric Mobile Robot, thin layers of piezoelectric materials are strategically incorporated into its structural framework.

These materials are carefully engineered to maximize their responsiveness to mechanical stimuli, enabling them to efficiently convert vibrational energy into electrical energy and vice versa. This capability forms the basis for the robot's locomotion mechanism, as it harnesses the inherent energy generated by the piezoelectric actuators to propel itself forward with remarkable precision and efficiency. The use of thin piezoelectric materials offers several distinct advantages for the mobile robot.

Firstly, their lightweight nature minimizes the overall weight of the robot, enhancing its manoeuvrability and agility. Additionally, their compact form factor allows for seamless integration into the robot's design, ensuring optimal efficiency and functionality. Moreover, the sustainable nature of piezoelectric materials aligns with the growing emphasis on eco-friendly technologies, making the robot an environ- mentally conscious solution for various applications.

In essence, the Piezoelectric Mobile Robot represents a paradigm shift in robotic design, capitalizing on the inherent properties of piezoelectric materials to achieve unparalleled efficiency and sustainability in locomotion. By harnessing the transformative power of these materials, this innovative robot opens up a myriad of possibilities for diverse applications, ranging from exploration and surveillance to environmental monitoring and beyond. As technology continues to evolve, the Piezoelectric Mobile Robot stands poised to lead the way towards a future where agility, efficiency, and sustainability converge to redefine the possibilities of robotic systems.

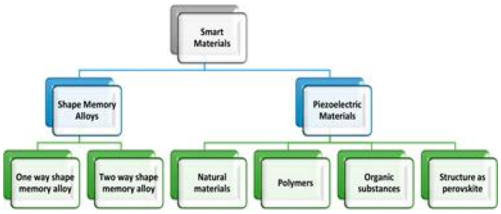

Fig. 1. Piezoelectric Materials

A. Curved Tail Oscillation Mechanism

The Curved Tail Oscillation Mechanism represents a paradigm shift in robotic locomotion, departing from traditional rigid tail designs to introduce a dynamic and versatile approach. Here's an elaboration on this innovative mechanism:

1) **Dynamic Oscillatory Motion:** Unlike static or rigid tails commonly found in traditional robotic designs, the curved tail oscillation mechanism introduces dynamic oscillatory motion. This means that instead of remaining fixed in position, the tail of the robot is capable of moving in a rhythmic manner, akinto the undulating motion observed in certain animal species.
2) **Curved Trajectory:** What sets this mechanism apart is itsability to execute oscillations along a curved trajectory. This curvature is not incidental but purposeful, allowing the robot tonavigate through complex environments with greater precisionand efficiency. By following a curved path, the robot cannegotiate obstacles, make sharp turns, and adapt to changesin terrain more effectively.
3) **Enhanced Agility and Manoeuvrability:** The dynamicoscillations along a curved trajectory confer several advantagesto the robot's agility and manoeuvrability. By modulating the curvature and frequency of tail oscillations, the robot can execute intricate movements with remarkable fluidity and grace. This enhanced agility enables the robot to traverse narrow passages, navigate uneven terrain, and respond swiftly to changing environmental conditions.
4) **Improved Stability:** Contrary to the misconception that oscillatory motion may compromise stability, the curved tail oscillation mechanism actually enhances the robot's stability. The rhythmic undulations of the tail serve to stabilize the robot's body, counteracting perturbations and maintaining equilibrium, particularly in challenging terrain or adverse weather conditions.
5) **Adaptability to Diverse Environments:** The versatility of the curved tail oscillation mechanism enables the robot to adapt seamlessly to diverse environments. Whether traversing rugged terrain, navigating cluttered indoor spaces, or manoeuvring through aquatic environments, the robot can adjust its tail oscillations to suit the specific demands of the surroundings, thereby expanding its range of applicability and utility.
6) **Integration with Control System:** The effectiveness of the curved tail oscillation mechanism is further enhanced through integration with the robot's control system. Advanced algorithms govern the coordination between tail oscillations, propulsion mechanisms, and sensory feedback, ensuring harmonious locomotion and responsive behaviour in real-time.
7) **Potential for Biomimicry:** The design inspiration for the curved tail oscillation mechanism often draws from nature, particularly from observing the locomotion strategies employed by animals such as fish, snakes, or even insects. By emulating biological principles of movement, the mechanism exemplifies the concept of biomimicry, wherein engineering solutions are inspired by natural systems.

B. Structural Design and Integration

The structural design adheres to a minimalist philosophy, prioritizing simplicity and efficiency in component layout and assembly. This approach minimizes unnecessary weight and bulk while maximizing the robot's manoeuvrability and agility. Careful consideration is given to the selection of materials to ensure both lightweight construction and structural integrity. High-strength yet lightweight materials such as carbon fibre composites or advanced polymers are often favoured, providing the necessary rigidity to support the robot's components without compromising agility.

The structural framework is designed to accommodate modular integration of components, facilitating ease of assembly, maintenance, and potential up- grades. Each component, including the piezoelectric actuators and oscillatory mechanism, is precisely positioned within the framework to optimize functionality and streamline integration. Mounting points and reinforcements are strategically incorporated into the structural design to ensure secure attachment of components while minimizing stress concentrations. This helps distribute loads evenly throughout the framework, enhancing overall stability and longevity. Critical components, such as the control electronics and power sources, are housed within sealed enclosures to protect them from environmental hazards such as dust, moisture, or impact damage. These enclosures are seamlessly integrated into the structural frame- work, maintaining the robot's sleek profile while safeguarding its internal systems.

Thoughtful consideration is given to cable management and routing within the structural design to minimize clutter and potential interference with moving parts. Cable harnesses are neatly organized and routed through designated channels or conduits, optimizing reliability and reducing the risk of tangling or damage during operation. Ergonomic considerations are taken into account in the design of the structural framework to ensure accessibility for maintenance and servicing tasks. Access panels or hatches may be incorporated into the design, providing convenient access to in- ternal components without compromising structural integrity.

Prior to fabrication, the structural design undergoes rigorous analysis using finite element analysis (FEA) and simulation techniques. This helps identify potential stress points, optimize material distribution, and validate the design's performance under various operating conditions, ensuring robustness and reliability in real-world applications.

C. Piezoelectric Actuators

Piezoelectric actuators serve as the vital components driving the locomotion system of the robot, embodying a sophisticated fusion of materials science and engineering ingenuity. These actuators are strategically embedded within the robot's structure, strategically positioned to optimize propulsion and manoeuvrability. Utilizing the remarkable properties of piezo- electric materials, such as piezoelectric ceramics or polymers, these actuators possess the unique ability to convert electrical energy into mechanical motion and vice versa. When subjected to an electric field, piezoelectric materials undergo deformation, resulting in precise vibrations or oscillations. This phenomenon forms the basis of their functionality as actuators within the robot. Within the robot's intricate design, the piezoelectric actuators are meticulously integrated to harness their transformative potential effectively.

Through a carefully orchestrated sequence of electrical signals, the actuators induce controlled vibrations or oscillations, generating propulsive forces that drive the robot forward with remarkable efficiency. The precise nature of these vibrations enables the robot to navigate diverse terrains with agility and precision, adapting its movements in real-time to changing environmental conditions.

Moreover, the inherent energy efficiency of piezoelectric materials ensures that the robot operates with minimal power consumption, prolonging its operational lifespan and reducing environmental impact. In essence, the piezoelectric actuators represent the cornerstone of the robot's locomotion system, embodying the synergy between cutting-edge materials science and innovative engineering. Through their seamless integration and precise control, these actuators enable the robot to achieve unprecedented levels of agility, efficiency, and manoeuvrability, setting a new standard for mobile robotic systems.

D. Tail Oscillation Dynamics

Tail oscillation dynamics refer to the coordinated movement of the robot's curved tail in response to the activation of piezoelectric actuators, resulting in controlled propulsion and manoeuvrability. The tail oscillation mechanism is designed to work harmoniously with the piezoelectric actuators, ensuring synchronized motion. As the actuators induce vibrations within the robot's structure, these vibrations are transmitted to the curved tail, causing it to oscillate in a controlled manner. The curvature of the tail allows for dynamic responses to changes in the robot's environment. When navigating uneven terrain or encountering obstacles, the tail can adjust its oscillatory motion to maintain stability and trajectory control, enhancing the robot's overall agility.

The frequency and amplitude of tail oscillations can be modulated to suit the specific requirements of the task at hand. By adjusting these parameters, the robot can achieve varying degrees of propulsion force and directional control, allowing for precise navigation even in challenging conditions. The ability to modulate tail oscillations enhances the robot's manoeuvrability, enabling it to perform intricate movements such as turning, pivoting, and reversing with ease. This level of agility is particularly advantageous in confined spaces or complex environments where traditional wheeled or tracked robots may struggle to navigate.

Tail oscillation dynamics enable adaptive navigation strategies, where the robot can dynamically adjust its motion in response to real- time sensor feedback. For example, if the robot detects an obstacle in its path, it can quickly alter the frequency and amplitude of tail oscillations to manoeuvre around the obstacle while maintaining forward momentum. The curvature of the tail contributes to the robot's stability by providing additional points of contact with the ground. This stability, combined with the precise control afforded by tail oscillation dynamics, allows the robot to traverse uneven terrain with confidence, minimizing the risk of tipping or losing traction.

E. Control and Navigation System

The Control and Navigation System of the piezoelectric mobile robot serves as its central intelligence, managing every aspect of its locomotion and ensuring efficient navigation through diverse environments. The control system receives sensory input from various sources, including on- board cameras, proximity sensors, and inertial measurement units (IMUs). These sensors continuously monitor the robot's surroundings, providing real-time data on terrain features, obstacles, and environmental conditions. Advanced algorithms analyse the sensory input to create a detailed map of the robot's environment. By leveraging computer vision techniques, LiDAR scanning, and depth sensing technologies, the system can accurately identify obstacles, terrain variations, and navigable pathways. Based on the environmental data gathered, the control system generates optimal navigation paths and makes informed decisions regarding the robot's movements. This involves selecting the most efficient route while considering factors such as terrain roughness, obstacle density, and energy consumption. The control system continuously monitors the robot's performance and dynamically adjusts its trajectory in real-time. By analysing feedback from the piezoelectric actuators and tail oscillation dynamics, the system can fine-tune motion parameters to optimize efficiency, stability, and manoeuvrability. Using a combination of reactive and predictive techniques, the control system enables the robot to navigate around obstacles autonomously. Reactive methods involve immediate adjustments in response to detected obstacles, while predictive algorithms anticipate future obstacles and plan pre-emptive manoeuvres accordingly. The control system operates within a closed-loop feedback mechanism, where sensor data is continuously compared against desired motion trajectories. Any deviations from the intended path prompt corrective actions, ensuring that the robot maintains precise control over its movements. Through the integration of advanced artificial intelligence (AI) algorithms, the control system enables the robot to operate autonomously in dynamic environments. By learning from past experiences and adapting to changing conditions, the robot can navigate complex scenarios with minimal human intervention. While capable of autonomous operation, the control system also includes provisions for human intervention and supervision. A user-friendly interface allows operators to monitor the robot's status, intervene when necessary, and provide high- level commands or way points for mission planning.

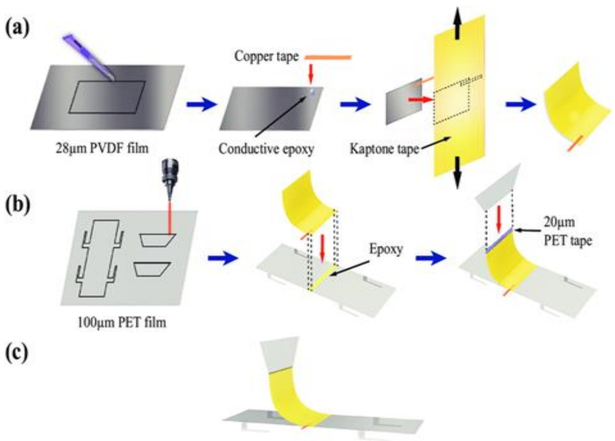

Fig. 2. Fabrication Process

6. Potential Applications

The potential applications of the piezoelectric mobile robot are vast and diverse, owing to its unique combination of features including compact size, manoeuvrability, and energy efficiency. In disaster-stricken areas such as collapsed buildings or rugged terrains, the piezoelectric mobile robot can navigate through tight spaces and rubble, providing vital assistance in locating and rescuing survivors. Its agility and ability to traverse challenging environments make it a valuable asset for search and rescue teams. The robot's compact size and silent operation make it well-suited for clandestine surveillance missions in urban environments, industrial facilities, or border areas. Equipped with cameras and sensors, it can gather real- time intelligence without attracting attention, enhancing security measures and threat detection capabilities. In remote or hazardous environments, such as forests, jungles, or polluted industrial sites, the robot can serve as a versatile tool for environmental monitoring. Equipped with sensors for detecting pollutants, temperature, humidity, and other environmental parameters, it can collect valuable data for scientific research, pollution control, and conservation efforts. The robot's manoeuvrability and ability to access confined spaces make it ideal for inspecting infrastructure such as pipelines, bridges, and tunnels. By navigating through tight spaces and conducting visual inspections, it can identify potential structural defects or maintenance issues, enabling timely repairs and preventing costly accidents. n agricultural settings, the robot can be deployed for tasks such as crop monitoring, pest control, and soil analysis. Equipped with specialized sensors and actuators, it can autonomously navigate through fields, identifying crop health issues, applying targeted treatments, and optimizing agricultural practices for improved yields and sustainability. In healthcare facilities or disaster zones, the robot can assist medical personnel by delivering supplies, conducting remote patient monitoring, or disinfecting surfaces. Its compact size and manoeuvrability enable it to navigate through crowded hospital corridors or confined spaces, providing valuable sup- port in emergency situations. Within industrial settings such as warehouses or manufacturing plants, the robot can automate material handling tasks, inventory management, and quality control inspections. Its ability to navigate efficiently through crowded spaces and interact with machinery makes it a cost- effective solution for streamlining production processes and improving operational efficiency. The robot can also serve as an educational tool for students and researchers interested in robotics, materials science, and renewable energy technologies. By providing hands-on experience with piezoelectric materials and robotic systems, it can inspire future generations of scientists and engineers to explore innovative solutions to real-world challenges.

7. Future Development and Enhancements

As the field of robotics continues to evolve, the future development and enhancement of the piezoelectric mobile robot hold significant promise for unlocking new capabilities and applications. Ongoing research efforts will focus on re- fining and optimizing the control algorithms governing the piezoelectric mobile robot's movements. Advanced machine learning techniques, such as reinforcement learning and neural networks, may be employed to enable the robot to adapt to dynamic environments more effectively. By continuously learning from its interactions with the surroundings, the robot can enhance its decision-making capabilities and improve overall performance. The integration of advanced sensor technologies presents an exciting opportunity to augment the piezoelectric mobile robot's perception and awareness of its surroundings. In addition to traditional sensors such as cameras and Li- DAR, researchers may explore the incorporation of novel sensing modalities, such as thermal imaging, chemical sensors, and acoustic sensors. These enhancements would enable the robot to gather richer environmental data, enhance situational awareness, and facilitate more sophisticated navigation and interaction with its surroundings. The versatility and agility of the piezoelectric mobile robot make it well-suited for a wide range of applications beyond its initial scope. Future research endeavours may focus on exploring novel applications in fields such as search and rescue, environmental monitoring, agricultural automation, and infrastructure inspection. By leveraging its compact size, energy efficiency, and manoeuvrability, the robot can assist in tasks that are inaccessible or hazardous to humans, thereby enhancing operational efficiency and safety. Another area of interest for future development lies in the integration of multi-robot systems, where multiple piezoelectric mobile robots collaborate and coordinate their actions to achieve common objectives. By leveraging swarm intelligence principles and distributed control algorithms, these robot teams can exhibit emergent behaviours and collectively accomplish complex tasks, such as collaborative exploration, surveillance, or disaster response. The scalability and flexibility of such multi-robot systems hold tremendous potential for enhancing efficiency and resilience in various real-world scenarios. Inspired by nature's ingenuity, future research may delve into bio-inspired design principles to further enhance the performance and adaptability of the piezoelectric mobile robot. By studying the locomotion strategies of animals and insects, researchers can derive insights into efficient movement mechanisms, morphological adaptations, and energy- efficient propulsion methods. Integrating bio-inspired features into the robot's design could lead to significant advancements in agility, robustness, and energy efficiency, opening up new possibilities for exploration and innovation.

8. Conclusion

The development of the thin piezoelectric mobile robot with a curved tail oscillation mechanism represents a significant milestone in the field of robotics. This innovative invention harnesses the unique properties of piezoelectric materials and dynamic tail oscillation to create a versatile, agile, and energy-efficient robotic platform with diverse applications. Throughout this project, we have explored the intricate design principles, operational mechanisms, and potential applications of the piezoelectric mobile robot. From its compact and lightweight construction to its sophisticated control and navigation systems, every aspect of the robot has been meticulously engineered to optimize performance and functionality. The integration of thin piezoelectric materials offers numerous advantages, including enhanced energy efficiency, reduced environmental impact, and increased manoeuvrability. By leveraging the piezoelectric effect for propulsion, the robot minimizes its reliance on traditional power sources, making it well-suited for long-duration missions in remote or resource- constrained environments. Furthermore, the incorporation of a curved tail oscillation mechanism adds a dynamic element to the robot's locomotion, enabling agile movement across diverse terrains and obstacles. This innovative design feature enhances the robot's stability, manoeuvrability, and adaptability, making it suitable for a wide range of applications, from search and rescue operations to environmental monitoring and beyond. Looking ahead, future research and development efforts will focus on further optimizing the robot's performance, expanding its capabilities, and exploring new avenues for application. By refining control algorithms, integrating advanced sensor technologies, and embracing bio-inspired design principles, researchers can unlock the full potential of the piezoelectric mobile robot and pave the way for transformative advancements in robotics.

Refrences

[1] Pan, Chi Hsiang, Sz Sheng Tzou, and Ruei Yang Shiu. "A novel wireless and mobile piezoelectric micro robot." In 2010 IEEE International Conference on Mechatronics and Automation, pp. 1158-1163. IEEE, 2010.
[2] Yan, Shaoze, Fuxing Zhang, Zhen Qin, and Shizhu Wen. "A 3-DOFs mobile robot driven by a piezoelectric actuator." Smart materials and structures 15, no. 1 (2005): N7.
[3] Li. J, Deng. J, Zhang. S, Chen. W, Zhao. J and Liu. Y. "Developments and Challenges of Miniature Piezoelectric Robots": A Review. Advanced Science, 10(36), p.2305128.(2023).
[4] Wang. L, Shu. C, Jin. J and Zhang. J. "A novel traveling wave piezoelectric actuated tracked mobile robot utilizing friction effect". Smart Materials and Structures, 26(3), p.035003.(2017).
[5] Yi. J. "A piezo-sensor-based "smart tire" system for mobile robots and vehicles". IEEE/ASME transactions on mechatronics, 13(1), pp.95-103. (2008).
[6] Hariri. H.H, Soh. G.S, Foong. S.H, Wood. K.L and Otto. K. "Miniature piezoelectric mobile robot driven by standing wave". In Proceedings of the 14th IFToMM World Congress (pp. 325-330). (2015, October).
[7] Zhou. J, Suzuki. M, Takahashi. R, Tanabe. K, Nishiyama. Y, Sugiuchi. H, Maeda. Y and Fuchiwaki. O. "Development of a -type mobile robot driven by three standing-wave-type piezoelectric ultrasonic motors". IEEE Robotics and Automation Letters, 5(4), pp.6717-6723. (2020).
[8] Lim. H, Kim. S.W, Song. J.B and Cha. Y. "Thin Piezoelectric Mobile Robot Using Curved Tail Oscillation". Ieee Access, 9, pp.145477-145485. (2021).
[9] Abondance. T, Jayaram. K, Jafferis. N.T, Shum. J and Wood. R.J. "Piezoelectric grippers for mobile micromanipulation". IEEE Robotics and Automation Letters, 5(3), pp.4407-4414. (2020).
[10] Aoshima. S.I, Tsujimur. T and Yabuta. T. "A miniature mobile robot using piezo vibration for mobility in a thin tube". (1993).