engineering proceedings

MDPI

Proceeding Paper

Design and Optimization of Mobile Microrobots with Piezoelectric Actuation for High-Precision Manipulation †

Jitendra Adhikari

Department of Mechanical Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India; Centre of Excellence in Product Design and Smart Manufacturing, Maulana Azad National Institute of Technology, Bhopal, Madhya Pradesh, 462003, India
jitendraadhikari42@gmail.com or 20003748@iitb.ac.in

† Presented at The 11th International Electronic Conference on Sensors and Applications (ECSA-11), 26–28 November 2024; Available online: https://sciforum.net/event/ecsa-11.

Abstract: This study delves into the design and optimization of mobile microrobots tailored for tasks requiring sub-micrometer precision, addressing key challenges in the miniaturization and efficiency of microrobotic systems. Each microrobot is composed of a mobile platform, a manipulation unit, and a specialized end effector, collectively enabling them to perform a diverse array of operations on various surfaces. The mobile platforms provide three degrees of freedom (DOF) and can support loads ranging from 10 g to 500 g, with actuation based on the slip-stick principle. A novel configuration of the components offers promising characteristics, notably the low voltage required to drive the actuators, facilitating battery integration. The manipulation unit incorporates actuators that utilize a combination of electric motors and piezoelectric materials. The study reveals that ceramic-based PZT-5H exhibits superior actuation performance, achieving significantly greater displacement compared to other materials, such as PVDF. Furthermore, the research highlights the importance of platform design and material selection in enhancing actuation efficiency and optimizing voltage application. These findings contribute to the development of more efficient manipulation units, emphasizing the potential for further advancements in compact and high-performance microrobots. The insights gained are critical for the ongoing miniaturization and optimization of these systems, particularly in precision applications where both accuracy and efficiency are paramount.

Keywords: micro robots; piezoelectric; actuation

1. Introduction

A revolution in engineering is unfolding with the emergence of microrobots—tiny technological wonders that are set to transform industries such as medicine, manufacturing, and more [1]. These micro-scale machines, often smaller than a human finger, boast exceptional features including compactness, light weight, and cost-efficiency, making them ideal for tasks that are impractical or impossible for larger robots. Typically, microrobots have dimensions under 100 mm, ranging from just a few millimeters to a few centimeters [2].

A major force behind the progress of microrobotics is the use of piezoelectric technology, which converts electrical energy into mechanical motion. This allows microrobots to move with incredible precision and agility [3]. Originally developed for micro-positioning in scanning tunneling microscopy, piezoelectric materials have evolved over the years, enabling these robots to perform complex tasks such as fault detection, rescue operations, and even delicate surgeries within the human body [4].

One of the driving mechanisms that has enhanced microrobot performance is the stick-slip principle, a motion control method that fine-tunes the friction between the robot and its environment [5]. This allows for highly accurate movements and reduces the risk

Citation: Adhikari, J. Design and Optimization of Mobile Microrobots with Piezoelectric Actuation for High-Precision Manipulation. *Eng. Proc.* **2024**, *6*, x. https://doi.org/10.3390/xxxxx

Academic Editor(s): Name

Published: 26 November 2024

of unwanted vibrations. Continuous innovations in actuator designs and excitation methods have further refined this technique, resulting in faster, more precise motion, and improved load-bearing capacity. Traditionally, piezoelectric stick-slip actuators have been driven by sawtooth waveforms, but this approach requires high input voltages, generating excessive heat and lowering efficiency. To tackle this, Morita and his team designed a resonant-type actuator using multilayer piezoelectric ceramic transducers, which significantly boosted the system's efficiency. However, managing heat production continues to be a hurdle for wider applications [6].

To further enhance actuator capabilities, Nishimura developed a stick-slip actuator using a Langevin transducer made from hard-type PZT [7]. This innovation enabled high-speed operation with a simple design. Building on this, Hunstig explored various excitation modes to improve actuator output, finding that these new methods surpassed the traditional sawtooth waveform in terms of velocity [8]. Meanwhile, Zhang's team introduced an actuator with anisotropic friction surfaces, which prevented backward movement in one direction, boosting both load capacity and movement efficiency [9].

Numerous prototypes based on inertial stick-slip mechanisms have since been created. For instance, Nomura and Aoyama in 2007 developed a platform for scanning electron microscopy (SEM) that allows three-degree-of-freedom planar motion [10]. This compact and lightweight platform, with high precision, showcased the potential of microrobots in imaging and detailed analysis. In 2000, Jiang and colleagues proposed a design using two piezoelectric actuators in a single direction, enhancing the performance of inertial stick-slip motion [11]. Peng et al., in 2015, presented a linear actuator capable of precision positioning for dual objects, with a compact design that achieved long strokes and high resolutions, broadening the range of possible microrobot applications in manufacturing and assembly [12]. Additionally, Meyer et al. in 2005 described a slip-stick system for stepwise scanning, offering a simple yet reliable solution applicable in areas like microfabrication and materials testing [13].

Most prior research on stick-slip actuators has not focused on material optimization to improve actuation performance. In this current study, four different piezoelectric materials—$Pb[Zr_xTi_{1-x}]O_3$ (PZT-5H), $BaTiO_3$,-$(C_2H_2F_2)_n$- (PVDF) and PZT-4D are analyzed. These findings underscore the importance of selecting optimal materials for specific applications, such as medical diagnostics, environmental monitoring, and precision manufacturing. As microrobotic research advances, the field is poised for further innovations, particularly in the development of advanced materials, which will drive the creation of even more capable and versatile microrobots.

2. Structure and Operating Principle

Mobile microrobots possess the unique capability to maneuver freely across various surfaces, allowing them to perform a wide array of tasks. This mobility enables the robots to access assembly sites from different angles, enhancing their versatility. Each microrobot is composed of three core components: a mobile platform, a manipulation unit, and specialized end effectors. The mobile platform is designed to offer 3 degrees of freedom (DOF), enabling translational movement along the x-y plane and rotational movement around the z-axis. This movement is powered by a slip-stick mechanism [14].

A crucial element of the slip-stick motion platform is the guiding mechanism. When a voltage is applied to the piezoelectric actuator, it induces displacement and force, which are transferred to the guiding mechanism to move the platform.

Figure 1 illustrates the working principle of the piezoelectric stick-slip actuator, which is driven by a sawtooth wave voltage. The following steps summarize the operating process:

Step 1: Initially, the piezoelectric stack remains at its natural length with no voltage applied. Both the slider (depicted in green) and the frictional rod (in blue) remain stationary.

Step 2: As the external voltage is gradually applied from time t_0 to t_1, the slow deformation stage of the sawtooth wave begins. The stator slowly powers up and extends. Due to static friction, the slider moves in tandem with the stator during this phase.

Step 3: During the rapid deformation stage (t_1 to t_2), the stator quickly loses power and retracts to its original position. In this phase, the slider slips against the stator due to inertia, moving a small distance backward. Kinetic friction between the slider and the frictional rod causes this reverse movement. Repeating these steps produces continuous stepping motion, resulting in an overall effective displacement, x_S.

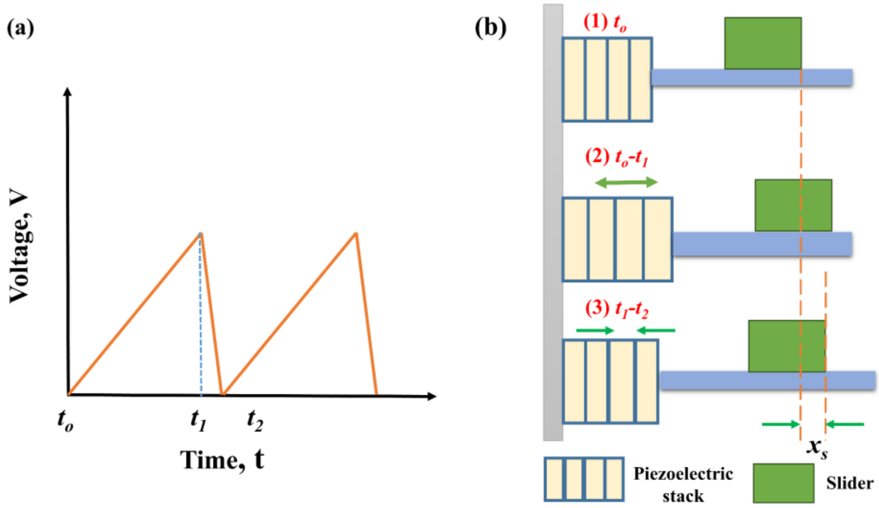

Figure 1. Working Mechanism of the Stick−Slip Actuator. (**a**) Schematic representation of the sawtooth excitation waveform. (**b**) Step−by−step depiction of the actuator's operation.

3. Results and Discussion

The stick-slip actuator operates using a sawtooth signal to drive the mobile platform. The manipulation unit integrates actuators that combine electric motors and piezoelectric materials. The performance of the platform actuator, however, relies heavily on the quality of the piezoelectric stack, with the material composition being a critical factor. To optimize the material selection for the best actuation performance, finite element analysis (FEA) is commonly employed in structural design and performance evaluation. In this study, COMSOL Multiphysics 6.2 is used for the FEA analysis.

For mobile platforms with dimensions ranging from 10 to 20 mm, the piezoelectric stacks need to be tailored to different load capacities. For larger platforms supporting loads of up to 500 g, the stacks typically have dimensions of 2–3 mm in length and width. Smaller platforms, which handle loads up to 50 g, use stacks with dimensions between 1–2 mm. The thickness of these stacks ranges from 1–2 mm for larger platforms and 0–1 mm for smaller ones. To achieve a balance suitable for platforms handling up to 500 g, a piezoelectric stack with dimensions of 2 mm in length and width and 1 mm in thickness was selected for the analysis.

Figure 2a presents the meshed piezoelectric stack, consisting of tetrahedral elements with 7,048 domain elements. This study examines four different piezoelectric materials—PVDF, PZT-5H, $BaTiO_3$, and PZT-4D—to determine the best actuation performance under a fixed applied voltage. For a sawtooth signal input with an amplitude of 20 V, as shown in Figure 1a, the resulting displacement or actuation is illustrated in Figure 2b, where PZT-5H was used. The material properties of the tested materials are summarized in Table 1.

Table 1. Stiffness and Piezoelectric Properties of Various Piezoelectric Stack Materials [15,16].

Material (Stiffness Properties	S_{11}^E	S_{12}^E	S_{13}^E	S_{33}^E	S_{44}^E	S_{66}^E

PVDF	378	−148.2	−172.4	1092	1110	1428
PZT-5H	16.5	−4.78	−8.45	20.7	43.5	42.6
$BaTiO_3$	8.05	−2.35	−5.24	15.7	18.4	8.84
PZT-4D	13.3	−4.76	−6.2	16.8	42	36.1
Material (Piezoelectric Properties	d_{31}	d_{15}	d_{33}	$\frac{\varepsilon_{11}^T}{\varepsilon_0}$	$\frac{\varepsilon_{33}^T}{\varepsilon_0}$	
PVDF	13.58	0	−33.8	7.74	7.74	
PZT-5H	−274	741	593	3130	3400	
$BaTiO_3$	−34.5	392	85.6	2920	168	

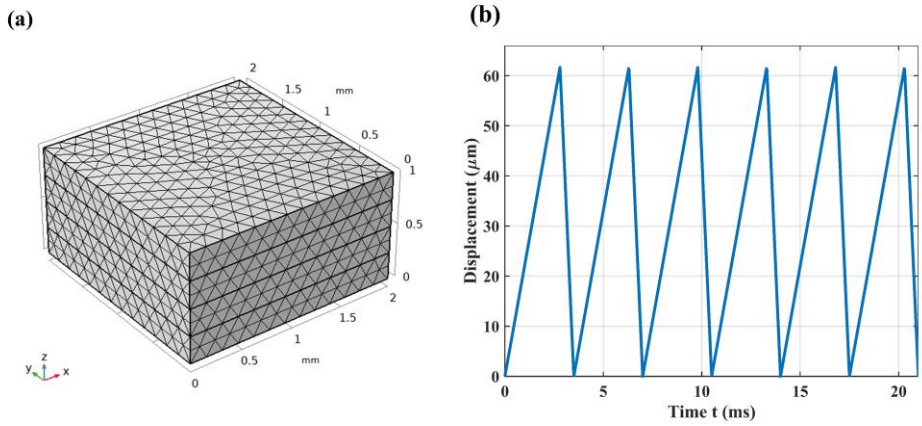

Figure 2. (**a**) Meshed cross-section of the piezoelectric stack. (**b**) Displacement output of PZT-5H in response to a sawtooth signal over time.

Figure 3 illustrates the impact of material selection on the actuation performance of the mobile robot platform, with a fixed 20 V saw tooth wave applied. Among the materials tested, PVDF exhibited the lowest actuation, while PZT-5H achieved the highest displacement of 61.73 µm. In fact, PZT-5H produced 16.6 times more actuation than PVDF and more than twice that of the second-best material, PZT-4D. Although PVDF is a flexible polymer, it delivers limited actuation due to its significantly lower piezoelectric coefficients compared to ceramic-based PZT-5H. The superior performance of PZT-5H is largely attributed to its remarkably high d_{31} and d_{33} coefficients, which not only enhance actuation but also make it ideal for energy harvesting applications.

Figure 3b further demonstrates the positive linear relationship between the applied voltage and the displacement generated by the mobile robot platform, showing that as the saw tooth voltage increases, the corresponding actuation displacement increases proportionally. This analysis is crucial for optimizing the selection of novel piezoelectric stacks in mobile robots, as it directly impacts their actuation performance. These insights can guide the design of more efficient and effective actuation systems for future mobile robotic platforms.

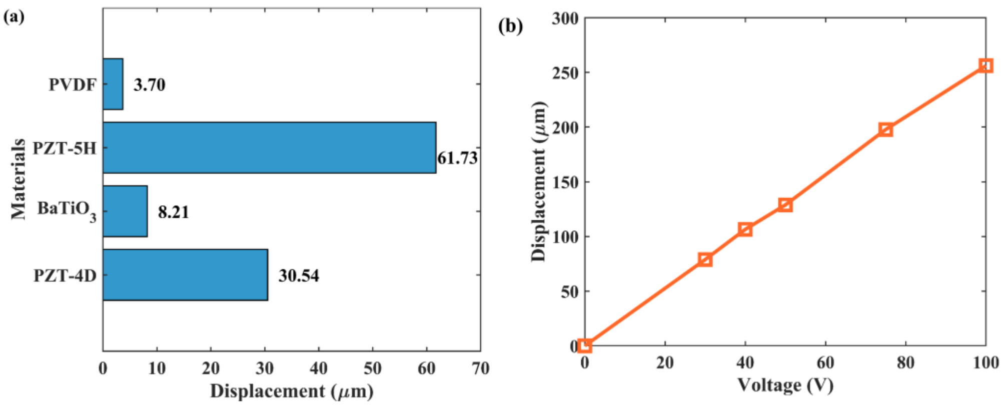

Figure 3. (**a**) Actuation performance comparison of various piezoelectric materials. (**b**) Actuation response of PZT-5H material as a function of applied voltage.

4. Conclusions

This study underscores the critical role of material selection in optimizing the actuation performance of mobile microrobots. By utilizing a piezoelectric stick-slip actuator powered by a sawtooth voltage signal, the microrobot platform achieves high mobility, enabling precise movement and versatility in various applications. The analysis highlights the superior performance of ceramic-based PZT-5H, which outperformed other materials, including flexible PVDF, by providing the highest displacement output of 61.73 µm. The exceptionally high piezoelectric coefficients (d_{31} and d_{33}) of PZT-5H make it ideal not only for enhanced actuation but also for potential energy harvesting applications. The finite element analysis conducted provided crucial insights into how material properties and structural dimensions affect actuation performance. The study demonstrated a positive linear relationship between applied voltage and displacement, reinforcing the importance of selecting high-performance piezoelectric materials for mobile robot platforms. These findings are vital for developing more efficient actuation systems, ultimately paving the way for advanced mobile robotic applications with improved precision and functionality. The results offer a pathway for future research into novel piezoelectric stack designs that optimize actuation and energy efficiency, supporting the development of next-generation mobile microrobots.

Funding: This research received no external funding.

Institutional Review Board Statement: NOT Applicable

Informed Consent Statement: Not applicable

Data Availability Statement: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Baines, R.; Patiballa, S.K.; Booth, J.; Ramirez, L.; Sipple, T.; Garcia, A.; Fish, F.; Kramer-Bottiglio, R. Multi-environment robotic transitions through adaptive morphogenesis. *Nature* **2022**, *610*, 283–289.
2. Fan, J.; Du, Q.; Dong, Z.; Zhao, J.; Xu, T. Design of the jump mechanism for a biomimetic robotic frog. *Biomimetics* **2022**, *7*, 142.
3. Adhikari, J.; Kumar, R.; Narain, V.; Jain, S.C. Electromechanical study of graphene reinforced lead-free functionally graded tile for vibration energy harvesting. *J. Intell. Mater. Syst. Struct.* **2023**, *34*, 861–876.
4. Pohl, D.W. Dynamic piezoelectric translation devices. *Rev. Sci. Instrum.* **1987**, *58*, 54–57.
5. Huang, H.; Zhao, H.; Yang, Z.; Mi, J.; Fan, Z.; Wan, S.; Shi, C.; Ma, Z. A novel driving principle by means of the parasitic motion of the microgripper and its preliminary application in the design of the linear actuator. *Rev. Sci. Instrum.* **2012**, *83*.
6. Morita, T.; Nishimura, T.; Yoshida, R.; Hosaka, H. Resonant-type smooth impact drive mechanism actuator operating at lower input voltages. *Jpn. J. Appl. Phys.* **2013**, *52*, 07HE05.

7. Nishimura, T.; Hosaka, H.; Morita, T. Resonant-type smooth impact drive mechanism (SIDM) actuator using a bolt-clamped Langevin transducer. *Ultrasonics* **2012**, *52*, 75–80.
8. Hunstig, M.; Hemsel, T. Drive signals for maximizing the velocity of piezoelectric inertia motors. *J. Korean Phys. Soc.* **2010**, *57*.
9. Zhang, Q.S.; Chen, X.B.; Yang, Q.; Zhang, W.J. Development and characterization of a novel piezoelectric-driven stick-slip actuator with anisotropic-friction surfaces. *Int. J. Adv. Manuf. Technol.* **2012**, *61*, 1029–1034.
10. Nomura, Y.; Aoyama, H. Development of inertia driven micro robot with nano tilting stage for SEM operation. *Microsyst. Technol.* **2007**, *13*, 1347–1352.
11. Jiang, T.Y.; Ng, T.Y.; Lam, K.Y. Optimization of a piezoelectric ceramic actuator. *Sensors Actuators A Phys.* **2000**, *84*, 81–94.
12. Peng, Y.; Cao, J.; Guo, Z.; Yu, H. A linear actuator for precision positioning of dual objects. *Smart Mater. Struct.* **2015**, *24*, 125039.
13. Meyer, C.; Sqalli, O.; Lorenz, H.; Karrai, K. Slip-stick step-scanner for scanning probe microscopy. *Rev. Sci. Instrum.* **2005**, *76*, 063706.
14. Kortschack, A.; Hänßler, O.C.; Rass, C.; Fatikow, S. Driving principles of mobile microrobots for micro-and nanohandling. In Proceedings of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003) (Cat. No. 03CH37453), Las Vegas, NV, USA, 27–31 October 2003; pp. 1895–1900.
15. Adhikari, J.; Kumar, R.; Narain, V.; Jain, S.C. Effect of Poling Orientation in Performance of Piezoelectric Materials. In *Machines, Mechanism and Robotics: Proceedings of iNaCoMM 2019*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 1721–1732.
16. Pryor, R.W. *Multiphysics Modeling Using COMSOL®: A First Principles Approach*; Jones & Bartlett Publishers: Burlington, MA, USA, 2009; ISBN 0763792330.