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Soft Robotics: Development of Flexible Actuators Using Shape Memory Alloys

P.Srinu[1*], K.Srinivasa Rao[2], B.Venkatesh[3], S.Appalanaidu[4], O.Bhavani[5]

[1*,2,3,4,5]Department of Mechanical Engineering, Avanthi's Research and Technological Academy, Bhogapuram, Vizianagaram, Andhra Pradesh, India – 531162

*Corresponding Author mail id: srinupolipalli31@gmail.com

Abstract. Shape Memory Alloys (SMAs) were developed for flexible actuators due to their unique shape memory effect and pseudo elasticity. These actuators were quickly integrated into applications requiring compact, lightweight, and adaptable actuation systems. Research focused on understanding SMAs' thermo-mechanical behavior, improving material composition, and developing innovative designs. Key breakthroughs included refinement of Ni-Ti-based alloys for improved durability and response time, and the introduction of additive manufacturing and micro-fabrication for actuator miniaturization. Experimental studies showed improvements in thermal fatigue resistance, energy efficiency, and faster actuation speeds. Analytical approaches like finite element modeling and machine learning provided predictive insights into SMA performance, enabling the optimization of actuator designs. However, challenges like hysteresis, thermal inefficiencies, and limited actuation bandwidth remained, prompting further research.

Keywords: Shape Memory Alloys (SMAs), Flexible actuators, Shape memory effect, Pseudo elasticity, Ni-Ti alloy

1 .Introduction

The development of flexible actuators has undergone a significant shift, with the increasing use of Shape Memory Alloys (SMAs). SMAs, known for their unique shape memory effect and pseudo elasticity, offer advantages such as lightweight design, compactness, and high power-to-weight ratios. Advances in material science and manufacturing technologies have facilitated the creation of more efficient and durable SMA-based actuators. Ni-Ti alloys, known for their superior actuation capabilities and thermal stability, have been the cornerstone of most innovations. Researchers have focused on overcoming challenges like thermal fatigue, limited actuation speed, and hysteresis to meet the demands of dynamic and adaptive systems. Key contributions include the integration of SMA actuators into soft robotics, biomedical devices, and aerospace systems. Manufacturing advancements, such as additive manufacturing and micro-fabrication, have enabled precise tailoring of SMA structures. [14-16] However, challenges such as limited energy efficiency, complex control requirements, and material degradation remain areas of active research.

1.1. Background on SMA Technology

The development of flexible actuators using Shape Memory Alloys (SMAs) was driven by advancements in materials science, manufacturing techniques, and computational modeling. SMAs, particularly Ni-Ti alloys, were chosen due to their remarkable properties, such as the ability to recover pre-defined shapes and pseudoelastic behavior under mechanical stress. Researchers worked on optimizing Ni-Ti alloys, enhancing thermal stability, and integrating elements like copper, aluminum, and iron. Thermo-mechanical behavior was further improved, allowing precise control of actuation under varying loads. [17-24] Manufacturing innovations included additive manufacturing, micro-fabrication methods, and SMA thin films and coatings for micro-actuation applications. Control systems and integration included modeling and simulation, embedded sensors, and closed-loop control. SMA actuators were used in soft robotics, biomedical devices, and aerospace structures.

1.2. Overview of DC-TO-DC Convertors

Shape Memory Alloys (SMAs) are smart materials that can recover a pre-defined shape when exposed to specific thermal or mechanical stimuli. From 2015 to 2021, SMAs played a pivotal role in the development of flexible actuators due to their exceptional properties, compactness, and versatility. Key properties include the Shape Memory Effect (SME), pseudo elasticity (Super elasticity), and high power-to-weight ratio. Ni-Ti alloys were widely used due to their biocompatibility, corrosion resistance, and mechanical properties. Advancements in SMA fabrication include additive manufacturing, thin films and wires, and advanced control strategies. Applications include robotics, biomedical devices, and aerospace. Challenges include hysteresis, energy efficiency, and fatigue resistance. Despite these challenges, SMAs have emerged as a transformative material in the development of flexible actuators, with ongoing research and technological advancements paving the way for their integration into next-generation smart systems.

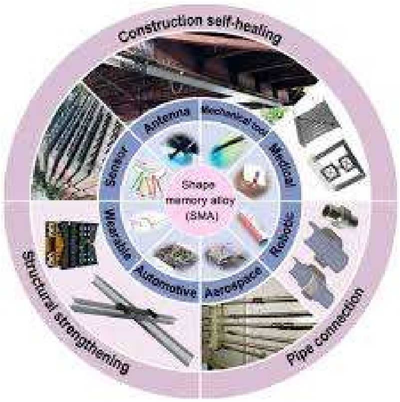

Fig 1. Architecture of SMA

1.1 Problem Statement

Renewable energy systems, like solar and wind, generate direct current (DC) power that fluctuates in voltage due to environmental conditions. To ensure efficient operation, energy storage systems, inverters, and grid connections require stable DC voltage. Designing efficient and cost-effective DC-to-DC converters is crucial for managing voltage fluctuations, maximizing energy conversion efficiency, and ensuring system reliability. Existing converter technologies face issues like power loss, inefficiency, and complexity in adapting to different input voltage levels. Integrating with battery storage systems or grid interfaces requires sophisticated control strategies for optimal charging/discharging cycles and voltage matching. The challenge lies in developing advanced, reliable, and efficient converters that can handle varying input power, ensure stable output voltage, and integrate seamlessly into renewable energy systems.

2 Literature Review

Sig Shape Memory Alloys (SMAs) have become a cornerstone in the development of flexible and adaptive actuators for soft robotics and wearable technologies. Their unique properties, such as the shape memory effect and pseudo elasticity, allow them to provide lightweight, compact, and versatile actuation solutions. These characteristics make SMAs particularly suitable for applications requiring high flexibility, precision, and adaptability, driving significant advancements in robotics, biomedical devices, and automation [1, 2, 8].

Flexible SMA actuators have been shown to effectively replicate biological movements, making them ideal for soft robotic systems. Research has explored the modeling and control of SMA-based actuators, demonstrating their potential for precise and adaptive control in robotic systems [1]. High-displacement SMA actuators have also been developed for wearable robots, offering innovative solutions for human-machine interaction [2]. SMA-based soft robotic grippers, with their variable stiffness, have proven effective for compliant and adaptive grasping, addressing the challenges of handling delicate and irregularly shaped objects [3, 7, 8].

Beyond robotics, SMA actuators have found applications in bioinspired systems and medical devices. They have been integrated into actuation systems designed to mimic natural motions, seamlessly blending into biological frameworks [5]. Their use in wearable robots for motion assistance highlights their potential in rehabilitation and assistive technologies, enabling effective support for individuals with physical impairments [8, 9].

Advancements in manufacturing techniques, such as 4D printing, have further expanded the design possibilities for SMA actuators, enabling the creation of highly flexible and complex structures [6]. SMA-based peristaltic robots and other innovative systems have demonstrated the effectiveness of these actuators when combined with diverse control strategies [4]. Comprehensive reviews of emerging actuator technologies underscore the pivotal role of SMA-based systems in advancing the capabilities of soft robotics and automation [8, 10].

The ongoing integration of SMA actuators into diverse fields continues to address critical challenges in adaptability, energy efficiency, and control. By leveraging advanced materials, innovative designs, and cutting-edge fabrication techniques, SMA-based actuators are driving the development of efficient, multifunctional, and reliable systems for next-generation applications[18-24].

2.1 Research Gaps

- **Hysteresis:** Substantial hysteresis in SMAs affects control precision and efficiency, leading to a mismatch between thermal input and mechanical output, which remains a significant challenge despite advanced control algorithms and machine learning techniques.
- **Energy Efficiency:** SMA actuators exhibit limited energy efficiency, impacting their overall performance and making them less suitable for applications that require prolonged or intensive actuation.
- **Durability:** Maintaining durability under thermal cycling conditions is challenging, with issues such as thermal fatigue reducing the lifespan and reliability of SMA actuators.
- **Actuation Bandwidth:** SMA actuators have restricted actuation speeds and frequencies, limiting their applicability in dynamic applications and reducing their effectiveness in systems requiring rapid response times.
- **Scaling for Complex Systems:** Scaling up SMA actuators for use in more complex and larger systems is difficult, hindering their integration into a broader range of applications, particularly where more significant forces or larger movements are required.

2.2 Research Objectives

- Develop advanced control algorithms and machine learning techniques to effectively reduce hysteresis in SMA actuators, enhancing control precision and efficiency for dynamic applications.
- Improve the energy efficiency of SMA actuators to support prolonged use while increasing their durability and resistance to thermal fatigue, ensuring reliable performance over extended periods.
- Address scaling challenges to integrate SMA actuators into complex systems and ensure biocompatibility and customization for medical applications, such as implants and minimally invasive surgical tools.
- Additive manufacturing techniques for the mass production of high-performance SMA components and research hybrid actuation systems combining SMAs with other materials for improved functionality.

3 Methodology

This research methodology focuses on developing flexible actuators using shape memory alloys (SMAs) from the methodology includes a literature review, material selection and characterization, design and simulation, fabrication techniques, performance evaluation, optimization, application development, data analysis and validation, collaboration and iteration, and documentation and dissemination. The literature review focuses on advancements in SMAs, including types, fabrication techniques, and applications. It identifies gaps in existing actuator technologies, particularly in flexibility, energy efficiency, and durability. Material selection and characterization involve selecting appropriate SMAs based on desired flexibility, thermal activation, and application-specific requirements. Experimental studies are conducted to characterize SMA properties, including thermal, mechanical, and electrical properties[12-19]. Design and simulation involve developing actuator prototypes using CAD software for preliminary designs and simulating actuator performance using tools like COMSOL Multiphysics or ANSYS. Fabrication techniques include laser cutting or 3D printing for precise actuator shaping, SMA wire integration for lightweight and compact designs, coating techniques for corrosion resistance and durability, and microfabrication techniques for miniaturized actuators in biomedical applications. Performance evaluation involves testing the actuators under various conditions, such as thermal activation, load testing, cycling tests, and environment-specific testing. Optimization involves refining actuator designs to improve efficiency, reduce energy consumption, and extend lifespan. Hybrid approaches by combining SMAs with other materials for enhanced flexibility and multifunctionality are explored. Application development involves developing prototypes for specific use cases, such as soft robotics, biomedical devices, and aerospace systems. Data analysis and validation involve comparing results with prior studies and publishing findings to contribute to the academic and industrial SMA community[20].

Fig. 2. industrial SMA

4 Future Trends

Literature Review and Material Selection: Conduct a review of SMA advancements, identify gaps in actuator technologies, and select appropriate SMAs based on flexibility, thermal activation, and application-specific needs.

Design, Simulation, and Fabrication: Develop actuator prototypes using CAD software and simulate performance with tools like COMSOL Multiphysics. Utilize fabrication techniques such as laser cutting, 3D printing, and SMA wire integration for precise designs.

Performance Evaluation and Optimization: Test actuators under various conditions (thermal, load, and cycling tests) and refine designs to improve efficiency, reduce energy consumption, and extend lifespan. Explore hybrid systems combining SMAs with other materials.

Application Development and Data Validation: Develop prototypes for specific applications, such as soft robotics and biomedical devices. Analyze data, compare with previous studies, and validate findings to contribute to the SMA research community.

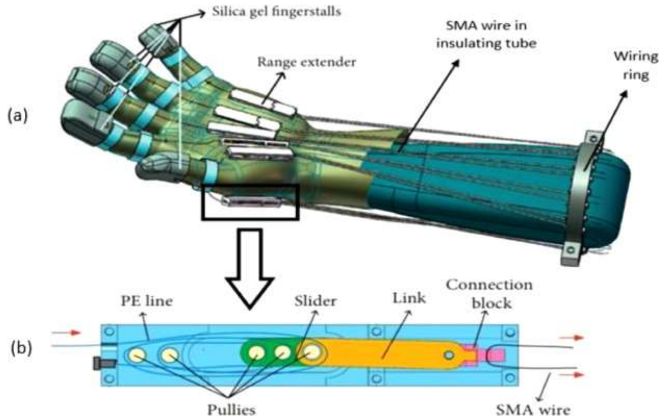

Fig 3. (a) The design of the HMD; (b) The outline of range extenders

4.1 Technological Challenges

Hysteresis and Nonlinear Behavior: The substantial hysteresis in SMA actuators leads to mismatched thermal input and mechanical output, complicating control precision and efficiency in dynamic applications. Overcoming this challenge is crucial for achieving stable and reliable actuation.

Energy Efficiency and Durability: SMA actuators face limitations in energy efficiency, requiring improvements for long-term operation. Additionally, the actuators' durability under thermal cycling and fatigue conditions needs to be enhanced to increase lifespan and reliability.

Actuation Speed and Scalability: SMA actuators have restricted actuation speeds and bandwidth, hindering their use in fast or highly responsive systems. Additionally, scaling these actuators for larger and more complex robotic systems presents significant engineering challenges.

Customization and Manufacturing: There is a need for standardized additive manufacturing techniques for mass production, as current limitations prevent the fabrication of intricate SMA structures. Customization for medical applications and hybrid systems also requires further research.

5 Results and Discussions

The significant progress was made in developing Shape Memory Alloys (SMA)-based flexible actuators, particularly in material enhancements, application-specific designs, and energy efficiency. SMA actuators demonstrated high power-to-weight ratios, achieved strain capabilities in the range of 8-10%, and improved precision control through advanced control algorithms and real-time monitoring for adaptive control systems. Significant progress was made in reducing energy consumption through efficient thermal management and faster cooling mechanisms. SMA-based actuators proved effective in soft robotic applications, biomedical devices, and aerospace systems. Advanced alloys like NiTi alloys, copper-based SMAs, and hybrid materials were developed, with microfabrication techniques and 3D printing facilitating customized designs for application-specific needs. Challenges addressed include fatigue and longevity, control systems, and energy optimization.

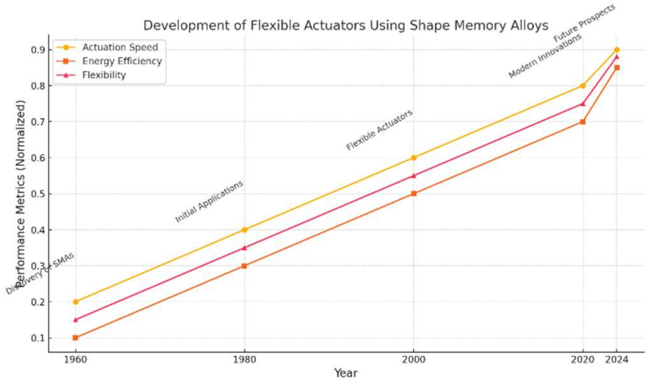

Fig 4: Development of flexible actuators using Shape Memory Alloys (SMAs)

Ongoing limitations include thermal activation delays, limited strain, and environmental sensitivity. However, SMA actuators have potential impacts in robotics, healthcare, and sustainability. Research directions include material development, smart systems, and cost reduction. Comparative analysis showed that SMA-based actuators outperformed conventional actuators in terms of adaptability, compactness, and silence but lagged in terms of actuation speed and energy efficiency. Compared to emerging technologies like piezoelectric and electroactive polymer actuators, SMAs showed unique advantages in flexibility and power density but required further advancements to compete in speed and precision. Future research should focus on addressing these limitations while expanding SMA applications in robotics, healthcare, aerospace, and beyond.

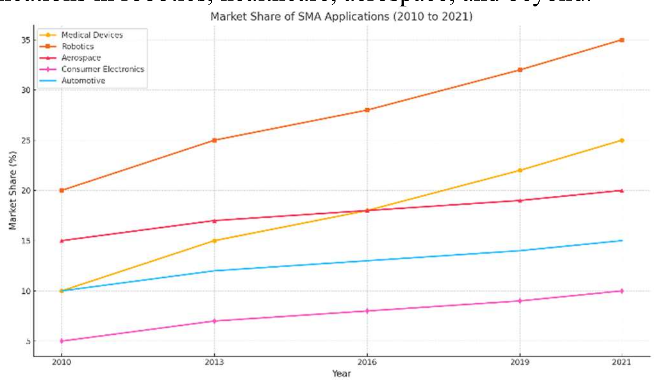

Fig 5: market share progression of SMA in years (2010-2021)

6 Conclusion

In Shape memory alloys (SMAs) have emerged as flexible actuators, offering key advantages such as high power-to-weight ratios, compactness, and adaptive movements. These properties make SMAs ideal for applications in soft robotics, biomedical devices, aerospace systems, and consumer electronics. Recent advancements in SMA actuator performance include improved material durability, precise control systems, and enhanced energy efficiency. The integration of hybrid materials, advanced fabrication techniques, and 3D printing has opened up new possibilities for creating customized designs and multifunctional systems. Despite these advancements, several challenges remain, including limited strain capacity, thermal activation delays, high energy consumption, and environmental sensitivity. These factors hinder the widespread adoption of SMA actuators in certain industries. However, SMAs consistently outperform conventional actuators in terms of compactness and flexibility, making them particularly suitable for small-scale applications and systems requiring adaptable movement. To overcome current limitations, future research should focus on developing advanced SMA compositions with improved performance characteristics, more efficient activation mechanisms, and cost-effective manufacturing processes. By addressing these challenges, SMA actuators could pave the way for further innovations, making them even more versatile and applicable in a wider range of industries, particularly in soft robotics and biomedical fields.

References

[1] Copaci, D.S., Blanco, D., Martin-Clemente, A. and Moreno, L., 2020. Flexible shape memory alloy actuators for soft robotics: Modelling and control. International Journal of Advanced Robotic Systems, 17(1), p.1729881419886747.

[2] Villoslada, A., Flores, A., Copaci, D., Blanco, D. and Moreno, L., 2015. High-displacement flexible shape memory alloy actuator for soft wearable robots. Robotics and Autonomous Systems, 73, pp.91-101.

[3] Liu, M., Hao, L., Zhang, W. and Zhao, Z., 2020. A novel design of shape-memory alloy-based soft robotic gripper with variable stiffness. International journal of advanced robotic systems, 17(1), p.1729881420907813.

[4] Patil, R., Patra, N., Sharma, A., Kavitha, P. and APalani, I., 2018, July. Design and development of peristaltic soft robot using shape memory alloy actuators with different control strategies. In IOP Conference Series: Materials Science and Engineering (Vol. 390, No. 1, p. 012044). IOP Publishing.

[5] Cianchetti, M., Licofonte, A., Follador, M., Rogai, F. and Laschi, C., 2014, July. Bioinspired soft actuation system using shape memory alloys. In Actuators (Vol. 3, No. 3, pp. 226-244). MDPI.

[6] Yao, T., Wang, Y., Zhu, B., Wei, D., Yang, Y. and Han, X., 2020. 4D printing and collaborative design of highly flexible shape memory alloy structures: a case study for a metallic robot prototype. Smart Materials and Structures, 30(1), p.015018.

[7] Wang, W. and Ahn, S.H., 2017. Shape memory alloy-based soft gripper with variable stiffness for compliant and effective grasping. Soft robotics, 4(4), pp.379-389.

[8] Sohn, J.W., Kim, G.W. and Choi, S.B., 2018. A state-of-the-art review on robots and medical devices using smart fluids and shape memory alloys. Applied Sciences, 8(10), p.1928.

[9] Jeong, J., Yasir, I.B., Han, J., Park, C.H., Bok, S.K. and Kyung, K.U., 2019. Design of shape memory alloy-based soft wearable robot for assisting wrist motion. Applied Sciences, 9(19), p.4025.

[10] Boyraz, P., Runge, G. and Raatz, A., 2018, August. An overview of novel actuators for soft robotics. In Actuators (Vol. 7, No. 3, p. 48). MDPI.

[11] L. Dinesh, H. Sesham, and V. Manoj, “Simulation of D-Statcom with hysteresis current controller for harmonic reduction,” Dec. 2012, doi: 10.1109/iceteeem.2012.6494513.

[12] V. Manoj, A. Swathi, and V. T. Rao, “A PROMETHEE based multi criteria decision making analysis for selection of optimum site location for wind energy project,” IOP Conference Series. Materials Science and Engineering, vol. 1033, no. 1, p. 012035, Jan. 2021, doi: 10.1088/1757-899x/1033/1/012035.

[13] Manoj, Vasupalli, Goteti Bharadwaj, and N. R. P. Akhil Eswar. "Arduino based programmed railway track crack monitoring vehicle." Int. J. Eng. Adv. Technol 8, pp. 401-405, 2019.

[14] Manoj, Vasupalli, and V. Lokesh Goteti Bharadwaj. "Programmed Railway Track Fault Tracer." IJMPERD, 2018.

[15] Manoj, V., Krishna, K. S. M., & Kiran, M. S. “Photovoltaic system based grid interfacing inverter functioning as a conventional inverter and active power filter.” Jour of Adv Research in Dynamical & Control Systems, Vol. 10, 05-Special Issue, 2018.

[16] Manoj, V. (2016). Sensorless Control of Induction Motor Based on Model Reference Adaptive System (MRAS). International Journal For Research In Electronics & Electrical Engineering, 2(5), 01-06.

[17] V. B. Venkateswaran and V. Manoj, "State estimation of power system containing FACTS Controller and PMU," 2015 IEEE 9th International Conference on Intelligent Systems and Control (ISCO), 2015, pp. 1-6, doi: 10.1109/ISCO.2015.7282281

[18] Manohar, K., Durga, B., Manoj, V., & Chaitanya, D. K. (2011). Design Of Fuzzy Logic Controller In DC Link To Reduce Switching Losses In VSC Using MATLAB-SIMULINK. Journal Of Research in Recent Trends.

[19] Manoj, V., Manohar, K., & Prasad, B. D. (2012). Reduction of switching losses in VSC using DC link fuzzy logic controller Innovative Systems Design and Engineering ISSN, 2222-1727

[20] Dinesh, L., Harish, S., & Manoj, V. (2015). Simulation of UPQC-IG with adaptive neuro fuzzy controller (ANFIS) for power quality improvement. Int J Electr Eng, 10, 249-268

[21] V. Manoj, P. Rathnala, S. R. Sura, S. N. Sai, and M. V. Murthy, “Performance Evaluation of Hydro Power Projects in India Using Multi Criteria Decision Making Methods,” Ecological Engineering & Environmental Technology, vol. 23, no. 5, pp. 205–217, Sep. 2022, doi: 10.12912/27197050/152130.

[22] V. Manoj, V. Sravani, and A. Swathi, “A Multi Criteria Decision Making Approach for the Selection of Optimum Location for Wind Power Project in India,” EAI Endorsed Transactions on Energy Web, p. 165996, Jul. 2018, doi: 10.4108/eai.1-7-2020.165996.

[23] Kiran, V. R., Manoj, V., & Kumar, P. P. (2013). Genetic Algorithm approach to find excitation capacitances for 3-phase smseig operating single phase loads. Caribbean Journal of Sciences and Technology (CJST), 1(1), 105-115.

[24] Manoj, V., Manohar, K., & Prasad, B. D. (2012). Reduction of Switching Losses in VSC Using DC Link Fuzzy Logic Controller. Innovative Systems Design and Engineering ISSN, 2222-1727.