

# A Critical Review of Emerging Trends in Shape Memory Alloy Actuators for Intelligent Robotics

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**Abstract:** Shape Memory Alloy (SMA) actuators have become a cornerstone in intelligent robotics due to their unique properties, such as compact design, noiseless operation, and high force-to-weight ratio. This paper critically reviews the advancements in SMA actuators, focusing on their material properties, design trends, and control strategies. Challenges like slow response time, energy inefficiency, and fatigue are analyzed alongside emerging solutions such as hybrid actuation systems, AI-based controls, and novel material formulations. The review concludes with future directions, including high-performance SMA development, AI integration, and additive manufacturing innovations.

**Keyword:** Shape Memory Alloy, Intelligent Robotics, Novel Material, Manufacturing

## INTRODUCTION

Shape Memory Alloys (SMAs) transform their shape upon thermal or electrical stimulation, making them ideal for compact robotic systems. Their high energy density and noiseless operation are key attributes driving their application in intelligent robots, including soft robotics, prosthetics, and micro-actuators (Lagoudas, 2008; Mohd Jani et al., 2014). However, challenges like limited thermal response time and material fatigue restrict their broader implementation (Miyazaki et al., 1986; Otsuka & Wayman, 1999). Shape Memory Alloys (SMAs) are a unique class of metallic materials known for their ability to recover a predefined shape after undergoing significant deformation. This remarkable behavior is governed by a reversible phase transformation between two crystallographic phases: martensite and austenite. When cooled below a specific transformation temperature, the alloy adopts the martensitic phase, allowing it to be easily deformed. Upon heating above this temperature, it reverts to its austenitic phase, recovering its original shape through a phenomenon known as the Shape Memory Effect (SME). Additionally, SMAs exhibit

superelasticity, enabling them to undergo large strains and recover without permanent deformation when stress is removed.

## Material Properties and Mechanisms

### Structure and Composition

Nickel-Titanium (NiTi) is the most popular SMA due to its excellent mechanical strength, biocompatibility, and superior shape memory effect. Recent advancements in Copper-based SMAs and high-temperature SMAs aim to address cost and temperature limitations (Duerig et al., 1990; Otsuka & Ren, 2005). Shape Memory Alloys (SMAs) possess a unique ability to undergo reversible phase transformations, which allow them to recover a predefined shape upon exposure to thermal or electrical stimuli. This exceptional characteristic is a result of their specific crystalline structure, primarily transitioning between martensite and austenite phases. The structure and composition of SMAs play a crucial role in determining their mechanical properties, transformation temperatures, and overall performance in various applications.

### Nickel-Titanium Alloys (NiTi)

Nickel-Titanium (NiTi) is the most widely utilized SMA due to its superior shape memory effect, biocompatibility, and excellent mechanical strength. NiTi alloys exhibit high recoverable strain (up to 8%) and exceptional corrosion resistance, making them ideal for biomedical and aerospace applications (Otsuka & Ren, 2005). The stoichiometric ratio of nickel to titanium significantly influences the transformation temperatures and the material's functionality. Variations in composition, such as Ni-rich or Ti-rich alloys, can be tailored to achieve specific operational characteristics, such as higher actuation temperatures or increased ductility (Miyazaki et al., 1986).

### Copper-Based SMAs

Copper-based SMAs, such as Cu-Zn-Al and Cu-Al-Ni alloys, have emerged as cost-effective alternatives to NiTi. These materials exhibit a lower cost of production and comparable shape memory properties; however, they are less durable and have reduced fatigue resistance. Their transformation temperatures are highly sensitive to compositional variations, and they are more prone to brittleness, limiting their use in high-stress applications (Otsuka & Wayman, 1999). Recent advancements in alloying and processing techniques aim to improve their mechanical properties and reliability for wider adoption.

### High-Temperature SMAs (HTSMAs)

The demand for SMAs capable of operating at elevated temperatures has led to the development of High-Temperature SMAs (HTSMAs). Alloys based on Nickel-Titanium-Hafnium (NiTiHf) and Nickel-Titanium-Palladium (NiTiPd) exhibit transformation temperatures above 100°C, making them suitable for automotive and aerospace applications where higher thermal stability is essential (Oliveira et al., 2020). Despite their enhanced thermal performance, these materials face challenges such as increased brittleness and higher production costs, which are active areas of research.

### Iron-Based SMAs

Iron-based SMAs, including Fe-Mn-Si alloys, are relatively new entrants in the field of smart materials. These alloys are characterized by their low cost, ease of processing, and moderate shape memory effect. Although they exhibit lower recovery strains compared to NiTi, their weldability and machinability make them promising candidates for large-scale applications, such as construction and industrial actuators (Lagoudas, 2008). Research is ongoing to enhance their functional properties and extend their application range.

### Nanostructured and Functionalized SMAs

The advent of nanotechnology has paved the way for the development of nanostructured SMAs, which offer improved transformation properties and durability. Techniques such as severe plastic deformation and thin-film deposition allow for the production of SMAs with tailored microstructures that exhibit enhanced fatigue resistance and faster response times. Functionalization of SMA surfaces

with coatings or nanomaterials is another growing trend aimed at improving corrosion resistance and extending service life (Saeed et al., 2020). SMA actuators rely on reversible martensite-austenite transformations, which provide a unique combination of shape recovery and mechanical work. This transformation is induced by heating or electrical resistive heating, offering silent actuation compared to electromagnetic motors (Paiva & Savi, 2006; Lagoudas, 2008).

### Current Trends in SMA Actuator Design

#### Miniaturization and Micro-Actuators

Micro-scale SMA actuators are widely used in biomedical devices, such as surgical tools and micro-grippers. Advances in fabrication techniques, like thin-film deposition, have improved precision and control (Pellegrino et al., 2018; Saeed et al., 2020). The trend toward miniaturization in robotic systems has led to a growing interest in the development of micro-actuators, particularly those based on Shape Memory Alloys (SMAs). These miniaturized actuators are essential for precision-driven applications, such as biomedical devices, micro-electromechanical systems (MEMS), and soft robotics, where compact size and high force-to-weight ratio are critical. SMA micro-actuators utilize the inherent phase transformation between martensite and austenite phases, enabling large deformations within small spatial constraints (Lagoudas, 2008). Micro-actuators have garnered attention for their potential to outperform traditional actuator technologies, including piezoelectric and electromagnetic systems, in specific use cases. Their noiseless operation, ability to function without complex mechanical components, and high energy density make them ideal for applications demanding minimal space and weight (Mohd Jani et al., 2014). However, the miniaturization of SMA actuators is not without challenges, including issues related to thermal management, energy efficiency, and precise control of actuation. Advances in fabrication technologies, such as thin-film deposition, laser micromachining, and additive manufacturing, have facilitated the creation of SMA micro-actuators with enhanced precision and scalability (Pellegrino et al., 2018). Researchers are also exploring hybrid micro-actuator designs that combine SMA properties with other mechanisms, such as piezoelectric actuation, to address the limitations of standalone SMAs. The integration of SMA-based micro-actuators into

robotic systems is particularly transformative in the biomedical domain, where they are used for minimally invasive surgical tools, micro-grippers, and drug delivery systems. These applications highlight the unique adaptability and precision offered by SMA micro-actuators (Saeed et al., 2020). Furthermore, the ongoing incorporation of AI-based control strategies is improving their performance by enabling real-time adjustments and reducing hysteresis effects. This section delves into the principles of miniaturization in SMA actuators, the advances in fabrication methods, and the application areas that are driving the adoption of micro-actuators in cutting-edge technologies. A critical analysis of the challenges and future opportunities in this domain is also presented, emphasizing the need for continued research in material innovation and control systems. Combining SMAs with other actuation mechanisms, such as piezoelectric actuators, compensates for their slow thermal response. These hybrid systems achieve enhanced performance in speed and efficiency (Ahn et al., 2012; Song et al., 2017). Machine learning and artificial intelligence are increasingly employed to overcome SMA hysteresis and enhance response times. Predictive control systems enable real-time adjustments to dynamic environments, improving robotic performance (Rizzello et al., 2018; Al-Ansary et al., 2020).

#### Challenges in SMA Actuators

The slow cooling and heating cycles of SMAs remain a significant limitation. Active cooling methods, such as liquid or thermoelectric cooling, have been explored to mitigate this issue (Mohd Jani et al., 2014; Oliveira et al., 2020). SMAs require high energy inputs for phase transitions. Researchers are investigating energy recovery systems and low-power designs to improve efficiency (Duerig et al., 1990; Zuo et al., 2022). Cyclic loading can degrade SMA performance over time. Coating technologies and alloy innovations are being tested to enhance durability and reduce fatigue (Otsuka & Ren, 2005; Song et al., 2017).

#### Applications in Intelligent Robotics

In soft robotics, SMAs are used to create flexible and compliant structures, such as robotic grippers, that mimic human hand movements (Kim et al., 2013; Saeed et al., 2020). Prosthetic limbs equipped with SMA actuators enable lifelike motion and adaptability. These actuators are also being integrated into wearable devices for rehabilitation (Pellegrino et

al., 2018; Zhang et al., 2023). Deployable robots for search and rescue missions utilize SMA-based actuators for their lightweight, silent operation, and ability to navigate confined spaces (Song et al., 2017; Rizzello et al., 2018).

#### Future Directions

Development of advanced SMAs with enhanced thermal and mechanical properties, such as Fe-based SMAs, is crucial for expanding their application range (Otsuka & Ren, 2005; Oliveira et al., 2020). AI-based systems for predictive modeling and control can address non-linearities and hysteresis in SMAs, making them more reliable for real-time applications (Rizzello et al., 2018; Al-Ansary et al., 2020). 3D printing allows the creation of customized SMA geometries, improving integration and functionality in robotic systems (Kim et al., 2013; Zhang et al., 2023).

#### CONCLUSION

Shape Memory Alloy actuators are at the forefront of intelligent robotics, offering unique advantages in terms of compactness, noiseless operation, and adaptability. Addressing challenges like energy inefficiency and material fatigue through innovative approaches, including AI integration and additive manufacturing, will unlock their full potential. Continued interdisciplinary research is essential for advancing SMA technology in robotics.

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