Minor Project Report

on

Design and development of shape memory alloy actuator for soft robotics

Submitted in the Partial Fulfilment of the Requirements for the Award of the Degree of

Bachelor of Technology

in

Mechatronics and Automation Engineering

By

Mr. Saket Kumar

(Roll No: 2001099)

Ms. Nishi Singh

(Roll No: 2001076)

Under the Supervision of

Dr. Tameshwer Nath

Assistant Professor

Department of Mechatronics and Automation Engineering

Indian Institute of Information Technology, Bhagalpur

BCE Campus, Sabour, Bhagalpur-813210

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DECLARATION

We hereby declare that the work reported in this thesis on the topic "**Design and development of shape memory alloy actuator for soft robotics**" is original and has been carried out by us independently in the **Department of Mechatronics and Automation Engineering, IIIT Bhagalpur** under the supervision of **Dr. Tameshwer Nath,** Assistant Professor, Department of Mechatronics and Automation Engineering, IIIT Bhagalpur. We also declare that this work has not been the basis for the award of any other Degree, Diploma, or similar title of any university or institution.

Saket Kumar
Roll No: 2001099

Nishi Singh
Roll No: 2001076

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CERTIFICATE

This is to certify that the thesis entitled "**Design and development of shape memory alloy actuator for soft robotics**" is carried out by **Saket Kumar (Roll No: 2001099) and Nishi Singh (Roll No: 2001076),** undergraduate student of IIIT Bhagalpur, under my supervision and guidance. This thesis has been submitted in partial fulfilment for the award of degree of **Bachelor of Technology** in **Mechatronics and Automation Engineering** at **Indian Institute of Information Technology, Bhagalpur**.

No part of this thesis has been submitted for the award of any previous degree to the best of my knowledge.

(Supervisor)
Dr. Tameshwer Nath
Assistant Professor
Dept. of Mechatronics and
Automation Engineering

(Head)
Dr. Abhinav Gautam
Assistant Professor
Dept. of Mechatronics and
Automation Engineering

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Saket Kumar
2001099

Nishi Singh
2001076

ABSTRACT

Shape memory alloys (SMAs) are a unique class of smart materials that can recover their original shape upon heating after being deformed. This shape memory effect occurs due to a temperature and stress-induced phase transformation between the low temperature martensite phase and the high temperature austenite phase. SMAs can generate substantial amounts of contractile or tensile stress during this transformation, allowing them to be used as compact solid-state actuators in various applications.

Compared to traditional actuators like motors and hydraulics, SMA actuators feature simpler designs, quieter operation, and relatively high power-to-weight ratios. Their ability to deliver large strokes in constrained spaces make them especially suitable for articulated robots and prosthetic devices. The biocompatibility and extreme corrosion resistance of some SMAs also enables their use for biomedical applications.

In this report, a comprehensive review is presented on research studies and prototypes over the past decade or so that have utilized SMAs as actuators across various types of robots. This includes bio-inspired crawling robots, jumping robots, flower robots, aquatic robots, walking robots, medical robots for procedures like endoscopy, as well as robotic limbs and grippers. For each robot sub-category, the specific advantages of using SMAs are discussed along with design considerations, implementation examples, and performance evaluation. Opportunities and challenges associated with SMA actuation technology are also identified.

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Chapter 1: Introduction

1.1. Overview

Soft robotics has gained prominence as a transformative field in robotics, offering innovative solutions for applications requiring adaptability, compliance, and interaction with delicate environments. In this context, the project focuses on designing and developing a Shape Memory Alloy (SMA) actuator, aiming to enhance the capabilities of soft robotic systems.

Shape Memory Alloys are chosen for their unique ability to undergo reversible deformation when subjected to temperature changes. Leveraging this property, the project seeks to create a novel SMA actuator that mimics the flexibility and resilience of natural muscles. The overarching goal is to contribute to the evolution of soft robotics by introducing a versatile actuator capable of efficient and adaptive movements.

The project methodology involves an in-depth exploration of SMA characteristics, encompassing phase transitions, thermal properties, and mechanical behaviour. This knowledge forms the basis for a meticulous design process, emphasizing the optimization of actuation speed, force output, and energy efficiency. The envisioned SMA actuator is intended to be compact, lightweight, and compatible with soft robotic structures, ensuring seamless integration into diverse applications.

Advanced manufacturing techniques, including 3D printing and specialized SMA processing, will be employed for prototype fabrication. Experimental testing will then validate the actuator's performance under various conditions, assessing its ability to replicate natural muscle movements and adapt to dynamic environments.

The broader impact of the project extends to potential applications in medical rehabilitation, wearable robotics, and minimally invasive surgical tools. By addressing the need for more versatile and adaptable actuators in soft robotics, the research outcomes aim to advance both theoretical understanding and practical implementation.

In summary, the project's overview highlights its commitment to advancing soft robotics through the design and development of a cutting-edge SMA actuator. By bridging the gap between theoretical knowledge and practical applications, this endeavour contributes to the ongoing evolution of soft robotic systems, offering new possibilities for improved functionality and real-world impact.

1.2. Introduction to soft robotics

Soft robotics is an emerging field of robotics that utilizes soft and deformable materials rather than traditional rigid materials in robotic design. Some key points about soft robotics:

Materials used include soft polymers, gels, fabrics, and other compliant materials that have flexible, deformable, and even stretchable properties. This allows for increased safety, adaptability, and resilience compared to hard robots.

Soft robots are inspired by nature and biology - for example octopus tentacles, elephant trunks, worms, and other flexible organisms are models for many soft robotic designs.

Control and actuation of soft robots involves pneumatic and hydraulic inflation, cable drives, smart materials that change shape with stimuli like heat or light, and other methods very different from motors and gears used to drive rigid robots.

Applications of soft robotics include grippers that can conform to pick up delicate objects, flexible surgical devices that won't damage biological tissue, wearable assistive devices, search and rescue snakes that can climb through rubble, and robots that can safely interact with humans.

Challenges in the field include modelling the dynamics and deformation of soft materials used, developing rapid soft actuators, incorporating sensors and controls, and improving manufacturability and durability.

So, in summary, soft robotics utilizes compliant, flexible materials and biologically inspired designs to create robots that are versatile, adaptable, and safe for interaction with humans and delicate tasks that conventional rigid robots struggle with. The field is still emerging but holds great promise.

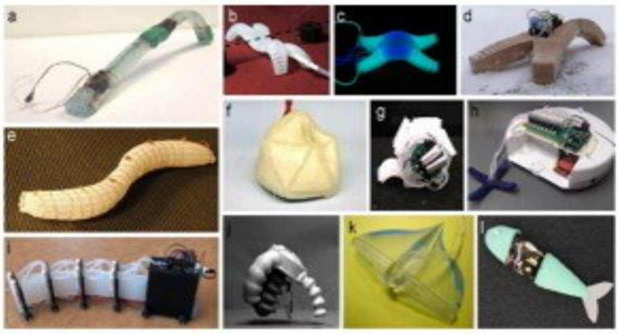


Fig 1.1. Soft robots

1.3. Introduction to shape memory alloy

Shape memory alloys (SMAs) are a unique class of smart materials that have the ability to return to a pre-programmed shape when heated. Some key introductory points about shape memory alloys:

They exhibit two unique properties - shape memory effect and super elasticity. The shape memory effect allows them to be deformed at lower temperatures but then resume their original "remembered" shape when heated above a transformation temperature.

Super elasticity allows SMAs to undergo large deformations with little residual strain. This allows them to act like springs or shock absorbers in applications.

Common shape memory alloys include copper-zinc-aluminium, copper-aluminium-nickel, and nickel-titanium alloys known as nitinol. Nitinol is the most used.

The shape changing ability of SMAs comes from a temperature-dependent shift in the alloy's crystal structure between a low-temperature martensite phase and a high-temperature austenite phase.

Shape memory behaviour can be "trained" into an SMA by heating it to high temps to take on a certain shape in its austenite phase, then cooling so it adopts a different shape in martensite. When reheated, the SMA will shift back to its trained austenite phase shape. This provides the shape memory effect. Applications of SMAs include actuators, microswitches, adjustable optical devices, medical implants, wearables, and damping devices like bracing reinforcements.

So, in summary, shape memory alloys are smart, functionally dynamic materials that can remember shapes, spring back from large deformation, and provide unique capabilities for actuation, sensing, and control.

It has been found that many materials exhibit the shape memory effect (SME), such as Cu-Zn, Cu-Zn-Se, Fe-Mn-Se, Au-Cd, etc. The most common SMA is a nickel-titanium alloy known as NiTiNOL. This SMA is believed to be one of the most important candidates for smart materials [3]. SMA based on Ni-Ti are the alloys most frequently used in commercial applications because they combine good mechanical properties with shape memory effect.

SMAs are usually available in the form of a wire, pipes, springs or ribbons. So, it can be used as a low-volume actuator in low-space where it is not possible to use huge actuator. In robotics, the SMAs represent a very interesting alternative within the field of classical drives, such as the electric or hydraulic motors. Thus, the drives based on metals with the shape memory effect are the subject of research in many institutions, which are interested in the research of robotics. In this paper, there are presented an assessment of application of SMA actuators in robotics' different branches such as crawler robots, jumper robots flower robots, fish robots, walker robots, medical robots and Bio-mimetic robotic hand.

1.4. SMA’S Driving Mechanism:

SMA actuators can drive standard robotic components like grippers, pumps, joints, and manipulators via linear or rotational movements. This space covers a broad application range from miniature connectors to wearable assistive devices.

The review highlights the extensive capabilities achievable with the high-power density of SMAs, ranging from miniature pumps to prosthetic fingers. Multiple SMA actuator topologies are discussed like contracted wires and coiled springs. Antagonistic setups using opposing SMAs demonstrate bidirectional and multi-degree-of-freedom movements.

Implemented controls span open loop testing to model-based strategies. While open-loop operation enables many functions, closed-loop methods like PID are often required to compensate for hysteresis and nonlinear dynamics. Recent works have incorporated feedback sensors to provide precise position and force control for applications like haptics and prosthetics.

Ongoing investigations continue to advance closed-loop control techniques to improve precision motion while optimizing form factor and response times. Efforts to enhance efficiency may unlock untethered and self-contained powered systems. Additional sensing and control could yield “smarter” systems.

Control Method	Features/Control Parameter	Application	Reference
Passive control	Strain to resistance modeling	Gripping fingers	Chao-Chieh et al., (2010) [49]
Passive control	Linear into angular movement	Three-fingered gripper	Khodayari et al., (2011) [50]
Passive Contol	Gripping force changes with the length of the flexure joint	Bio-inspired gripper	Gwang-Pil et al., (2011) [51]
Passive control	Differential actuation system	Connection	Guoqiang et al., (2012) [52]
Passive control	Variable pressure difference	Displacement pumps	Keerthi et al., (2013) [53]
Passive control	Gripping force distribution between the finger and the object	Soft robot gripper	Obaji and Zhang (2013) [54]
Fuzzy-PID control	Strain to differential resistance	1-DOF manipulator arm	Josephine et al., (2013) [55]
PI control	Bidirectional strain/displacement to step movement	Positioning device	Shinya et al., (2013) [56]
Fuzzy-PID control	Resistance feedback	Ball joint for end effector	Zhenyun et al., (2014) [57]
PWM control	Enhancement of force and control	SMA based motor	Rossi et al., (2014) [58]
Fuzzy sliding-mode control	Anti-slip control by force sensing	Robotic gripper	Shaw and Lee (2014) [59]
PID controller cascaded with a BPID	Position control	Position control	Álvaro et al., (2015) [60]
Fuzzy-SMC	Strain to position control	Ball balancing beam (underactuated)	Sunjai et al., (2015) [61]
Sliding mode control	Strain to differential resistance	1-DOF bidirectional servo actuation	Josephine et al., (2015) [62]
PI and saturated PI	Stiffness and compliance	Servomechanism	Zhao et al., (2015) [63]
PD control	Electrical resistance and force feedback (haptics)	Master-slave systems	Josephine et al., (2016) [64]
Passive control	Pulling and grasping	Three-fingered gripper	Wei et al., (2016) [65]
Passive control	Bending and load holding	Robotic hand	Hyung et al., (2016) [66]
PWM	Close and open	Gripper	Rad et al., (2016) [67]
Passive control	Actuation and variable stiffness	Robotic skin	Yuen et al., (2016) [68]
Passive control	Thermoconstitutive model deformation of the actuator	Curved gripper	Hugo et al., (2017) [69]
Higher-order SMC	Differential electrical resistance	1-DOF manipulator arm	Josephine et al., (2017) [70]
PWM	SMA resistance, self-feedback	Soft manipulator	Zhang et al., (2017) [71]
Passive control	Touch/pressure—shearing force	Haptic device	Lim et al., (2017) [72]
Passive control	Extension and flexion force	Prosthetic hand	Van der et al., (2017)[73]
PD control	Shape control based linear actuators -Active Cells	MACRO	Nawroj et al., (2017) [74]
Passive control	Adhesive pressure control	Gecko inspired gripper	Mehdi et al., (2018) [75]
Open-loop testing	Continuous and bidirectional rotation	Wearable rehabilitation	Hwang et al., (2018) [76]
PID control	Angular displacements with compliance	Soft bio-inspired robotic systems	Youngshik et al., (2019) [77]
Open-loop testing	Theoretical model of grasping force for different capturing targets.	Robotic gripper	Yifan et al., (2019) [78]
Open-loop control	Numerical and experimental responses of angular displacement, force, and torque	Servo drive (motor)	José et al., (2020) [80]
Data driven control	Displacement control	Rehabilitation medical devices	Zhang et al., (2020) [81]
ANFIS	Closed-chain serial mechanism	Bio-inspired and soft robotics	Mansour et al., (2020) [82]
Open-loop control	Active cooling system for efficient response	Wearable robotics	Joey et al., (2020) [83]
Open-loop control	Curvation variation	Foldable robot	Cordelia (2021) [84]
Backward Euler time integration algorithm and the prediction-correction technique	Euler time integration algorithm and the prediction-correction technique	SMA actuator	Esposito et al., (2021) [85]
PID control	Gripping force	Soft gripper	Wei et al., (2021) [86]

Table 1. Control methods of SMA as driving mechanisms.

Chapter 2: Application of SMA Actuator in Soft Robotics

Shape memory alloy (SMA) actuators find various applications in soft robotics due to their unique properties, making them suitable for creating versatile and adaptable robotic systems. Some key applications of SMA actuators in soft robotics include:

2.1. Crawler robots:

Liu and Liao [8] presented the development and testing of a snake robot that uses. SMAs as actuators in 2004. An eight-segment robot was designed to move similar to the rectilinear motion of a natural snake. A pair of SMA wires had been implemented into each segment. One of the SMA wires in each segment was heated at a time, and it acted like a muscle to change the shape of the segment. A prototype robot was built, and it could move well with the desired locomotion. As shown in Fig. 1, when the lower wire is activated, the distance between its two ends is extended to 4 cm, and the distance between its two ends of the upper wire is shorten to 2 cm.

In the same year, Lee et al [9] introduced a novel bio-mimetic micro robot with simple mechanism using SMA to generate earthworm-like locomotion, A two-way linear actuator using SMA spring and silicone bellows had been applied to the micro robot.

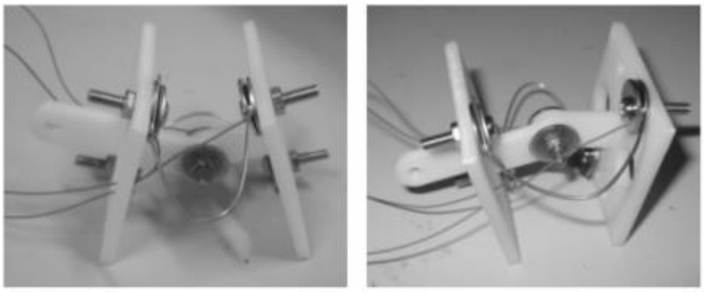


Fig 2.1. Segments with activated SMA wires

Fig. 2 shows the locomotive principle of the proposed micro robot. The front needles clamp a contact surface and the rear body slides forward when SMA spring is contracted by heating. After the contraction of the SMA spring, the deformation energy of the silicone bellows makes the SMA spring elongate when it cools. At that time, the rear needles clamp the contact surface and the front body slides forward. Finally, the bellows' spring force is equal to that of SMA spring as initial equilibrium state.

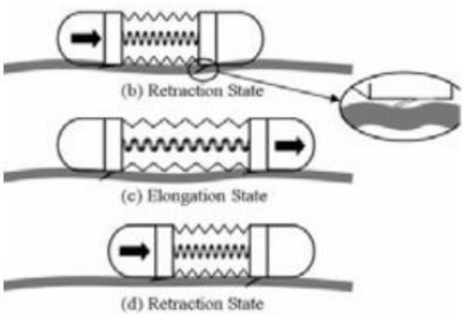


Fig 2.2. Principle of locomotion

Pipe inspection is a very important issue in construction. The inspection of low diameter canalizations is a pending issue nowadays; however, it would help to repair and maintain a large amount of installations. Conventional in-pipe moving mechanisms for pipe inspection, driven by electromagnetic motors, have large volume and mass. The SMA actuator can be an alternative for a small-sized in-pipe moving mechanism due to its great power-to-weight ratio and simple structure. In 2005, Gamboa et al [14] presented a robot that was able to move inside pipes of less than 26mm diameter and negotiate bends while carrying a camera to make an efficient in-pipe search. Each module of this robot had three degrees of freedom (DOF) with 3 SMA wires. Spring type SMA actuators are selected to fabricate an inchworm-like moving mechanism that consists of clamping and moving modules (Fig.3). For selection of proper operating type (a bias type or a differential type) for clamping module and moving module, displacements and dynamic characteristics of each operating type were investigated by Lee and Kim [19] in 2008. A moving speed of 34 mm/min and traction force of 0.4N were obtained from the driving experiment in a pipe with the diameter of 39mm.

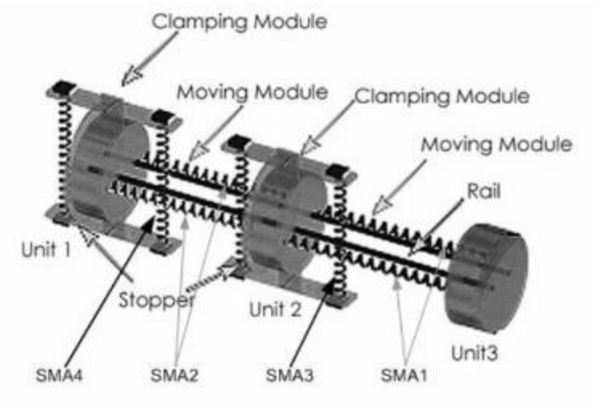


Fig 2.3. Structure of in-pipe moving mechanism

2.2. Jumper Robots:

While most mobile robots focus on continuous terrestrial snake-like or wheeled movement, discontinuous gaits like jumping help small robots overcome larger discrete obstacles and travel faster by increasing stride length. This is useful for navigating highly uneven terrain like rubble or debris.

By whole-body morphing, soft deformable robots without extensible limbs can execute such rapid jumps over multiple times their own height. Through dynamic simulations and hardware prototypes, distributing SMA actuator coils radially within the elastomer jacket or cage surrounding a rigid core allowed programmable deformation sequences that compressed the body before rapid release. This built-up substantial spring energy for achieving jumping motions.

For example, activating the lower half of SMA coils deformed the initially spherical robot into a hemispherical stance, while subsequently activating the upper half coils caused further compression into a disc shape from which the structure could springily jump up to 80 mm - over twice the robot's diameter. Alternating between crawling using multiple contact points and 30-40 mm jumps enabled the 3 kg spherical robots to negotiate obstacles and travel at over 200 mm/s, almost 70 times their diameter per minute.

Positioning additional dedicated jumping actuators on antagonistically to the crawling coils doubled the take-off velocity. Using variable stiffness SMAs could further optimize energy storage across deforming structural elements. Miniaturized versions of such deformable jumper robots can help access hazardous locations temporarily to gather data. However complex motion planning algorithms need to be developed to strategically sequence jumps to maximize speed and traversal range.

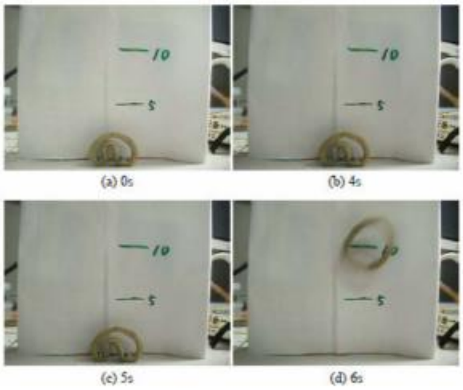


Fig 2.4. Circular soft robot jumping

2.3. Flower Robots:

Flower robots refer to a specialized category of home service robots designed to have an aesthetic biomimetic form and movement resembling flowers and plants to seamlessly blend into household décor when not actively being controlled. Social assistive capabilities expected from companion robots are also built into such devices.

The charming lifelike behaviour serves to improve emotional connections, trust, and psychological comfort between users and assistive robots. Since plants dynamically reorient, bloom, and extend parts like stems, leaves and petals to seek sunlight and spread seeds, these graceful movements can be replicated in flower robots using distributed SMA actuators.

The flowering motion was achieved using three radially arranged coil SMAs integrated into an artificial pistil, which could pull on the attached petals to open and close them with joule heating. The 50 mm long stem was similarly able to pull into a compressed helical shape or elongate into a straightened form using three embedded axial SMA coils connected to the tip. Leaf actuation used SMA wires affixed to their surfaces in a bending configuration.
Servo motors in the base enabled work volume adjustments, while sensors provided environmental feedback for stimulus-responsive behaviour. With their slender profile and nimble actuation, clusters of such flower robots could potentially be deployed for ambient environmental monitoring or home healthcare applications. However continuous SMA actuation consumes considerable power, so intelligent control is vital for energy efficiency.

Fig 2.5. The movement of stem and flower petal

2.4. Fish Robots:

Fish and aquatic animals like dolphins, seals, penguins etc. have evolved a variety of efficient swimming gaits by using muscles, fins and tails to push against water and generate thrust. Studying this hydrodynamic movement can provide useful insight into designing agile underwater drones. Robotic analogues seek to mimic such bio-inspired propulsion using flexible caudal fin actuators and paddles made from smart materials like SMA composites.

As constructed by \[Reference 25\], digitally fabricated biomimetic fish tails have an articulated spinal structure consisting of vertebral NiTi super elastic SMA sections connected by resilient epoxy joints. This provides requisite flexibility as well as springy recoil for oscillatory motion. Waterproof electroactive polymer skins attached to the SMA endoskeleton stretch under muscle-like actuation from the SMAs activated through joule heating, enabling tuneable stiffness fins to flap with life-like motion.

Directly embedded SMA wires on bio-inspired electroactive polymer fins to mimic musculoskeletal control, which bends along preset lines to generate propulsive forces. Strategically directing these forces in tailored sequences creates net thrust movement. For robotic fish approximately 15-20 cm in size, using 0.1-0.35 mm diameter SMA wires kept actuation voltages modest under 10V while enabling swift motion comparable to real fish.

The high corrosion resistance makes NiTi based SMAs well suited to prolonged underwater operation without degradation. Combining smart materials in this modular, scalable way provides a toolbox of responsive components - skeletal structures, muscles, skins, senses - for building agile aquatic drones that can inspect submerged structures or conduct environmental surveys. System integration of components with suitable waterproofing remains an area requiring further innovation.

Fig 2.6. Fish Robot

2.5. Walker Robots:

Legged robot locomotion has traditionally been technically challenging to achieve compared to wheeled motion, but provides greater mobility over uneven terrain, stairs, and rough inclines. Bio-inspired walking gaits require coordinated rhythmic multi-DOF joint actuation sequences that are hard to derive just from first principles. SMAs however can inherently produce lifelike forces and movement in a compact, noiseless package - making them well-matched to replicating biomechanical function in multi-legged walkers.

14-gram micro biped walker was developed that utilized flexible polymer body panels embedded with SMA wire actuators. Individually activating two wires per side tilted the panel to lift and swing each leg forward like thigh muscles. This
produced a dynamic gait allowing the tiny humanoid robot to walk at over 10 mm/s. While manoeuvrability was limited, the concept demonstrated very lightweight legged mobility.

Extending this idea, fabricated multi-segmented leg-like continuum manipulators entirely from SMAs. By differentially heating the three embedded titanium-nickel SMA actuator wires, the composite polymer legs would bend at desired angles with low power consumption to mimic animal motion. Integrating six such actuated legs in an alternating tripod gait let the 140-gram hexapod walker stably climb over obstacles higher than its 15 cm body height. With no rigid transmission mechanisms, the simplicity enabled miniature insect-scale walking robots.

Insect adhesion and climbing techniques were also studied to produce wall-gripping surface cleaning robots that can transition from crawling to stairs and vertical smooth surfaces. As prototyped by \[Reference28\], a quadruped gecko robot with toe pads and tail had panel joints independently actuated by SMA wires for each DOF. With this redundancy, even if certain actuators failed the robot could employ alternate gaits by adapting motion planning algorithms to continue movement. This highlights the fault tolerance arising from distributed bio-inspired actuation. However, the cycle lifetime of SMA wires undergoing repeated high frequency strain remains a practical limitation.

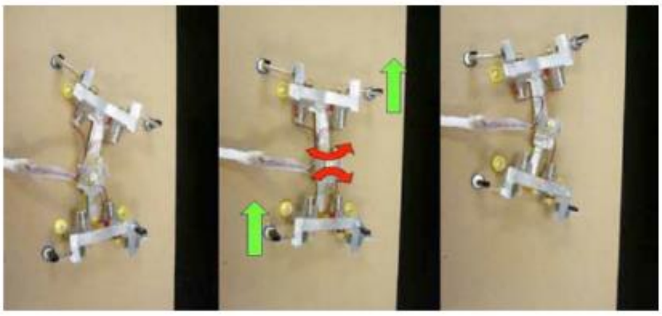


Fig 2.7. Locomotion of Rigid Gecko Robot

2.6. Medical Robots:

One of the other application areas of SMAs is in medical robots. In 1999, Reynaert et al [33] described a prototype gastro-intestinal intervention system based on an inch-worm-type of mobile robot which was a kind of vehicle for inspection through the colon. The robot consisted of three main modules that all these modules were actuated by SMA elements.

Also in 2001, Mi et al [34] presented the robot mainly consisted of soft mobile mechanism for earthworm locomotion and turning mechanism based on SME. The soft mobile mechanism contacted colon wall with air-in inflatable balloons, so the robot had better soft and non-invasive properties.

Medical procedures like gastrointestinal endoscopy traditionally rely on flexible cameras and instruments threaded through the body's organic pathways for diagnostic imaging and tissue sample retrieval respectively. But navigating the convoluted contours of tubular organs remains challenging. Self-propelled robotic capsules and worms that can crawl along these lumens through peristalsis while carrying modules for biopsy, drug delivery etc. allow doctors to painlessly access difficult sites.

The demands for compactness, smooth contours, and wireless mobility make SMAs an attractive option for medical device actuation inside the human body. As crafted an inchworm robot composed of multiple pivoting link modules joined end-to-end could extend and contract using SMA spring actuators. By coordinating the pulling and releasing actions of the distributed actuator elements, net rectilinear motion of the robot was achieved through anatomical conduits like the gastrointestinal tract.

Similar earthworm robots with 3-10 miniaturized track segments having 1-2 dedicated SMA wire coils each were designed for intestinal endoscopy, while colonoscopy robots used up to 6 antagonistic SMA actuators per segment. The spring steel SMA coils provided both structural support as well as actuation, while polymeric skins ensured biocompatibility. Some prototypes also incorporated inflatable bladders or micro-patterned cilia over limited areas to assist motion.

The redundant distributed actuation provides continuity of operation even if some subunits fail. Additionally, the micro robots could be equipped with detachable payloads like cameras, biopsy arms, UV disinfecting diodes, drug reservoirs etc. for intervention after diagnostic imaging. Current capabilities still fall short of practical utility thresholds in terms of speed, control, and incorporation of sensors. But the technology shows promise for future micro-robotic surgeries if scalability challenges can be overcome.

2.7. Robotic Hands:

Recreating the human hand's unique strength, finesse and sensation capabilities remains an enduring goal in robotic manipulation research, with promising applications from prosthetics to industrial wearable gloves. The numerous degrees of freedom, high forces, fine motor control, and haptic feedback involved poses complex design challenges using traditional actuators. SMAs on the other hand can mimic muscles remarkably well.

The super elasticity and silent, shock-absorbing operation of NiTi SMAs in particular help replicate the high strain tolerance and protective reflex actions of muscle-tendon networks in biological hands. 4-DOF robotic fingers having an aluminium proximal and middle phalanx were rotated using SMA wires attached to the distal joints. Each finger weighed only around 65 gm, while providing adaptively firm grasps using 350 kPa pressure - comparable to humans.

3D printable 15 gm 4-DOF artificial fingers were created based on anatomical bone shapes and dimensions. Routing SMA wires through the phalanges' hollow spline-jointed topology mirrored tendon paths, allowing responsive actuation of the finger joints for wrapping around irregularly shaped objects using just 0.5W power. Adding haptic sensors helped modulate grasping force. When integrated together into an articulated palm, impressive manipulation abilities emerged from the coordination of such independently controlled fingers purely via distributed control, validating the efficacy of the bio-inspired approach.

However, the low energy efficiency of SMAs limits battery-powered operation time. Combining high efficiency servo motors for major joint flexion with lower force SMA wire actuation of smaller joints balanced speed and strength while reducing total power consumption of the prosthetic hand by over 70% compared to SMAs alone. Such selective hybrid actuation that takes advantage of SMA strengths where most appropriate may enable better real-world utility. Redundancy and safety need to be investigated as well for medical approval.

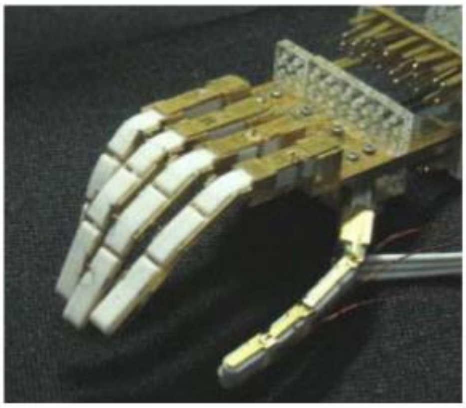


Fig 2.8. Developed five-fingered robotic hand

Chapter 4: Proposed Idea

We present a novel soft robot actuator that comprises a pre-stressed elastomer film embedded with shape memory alloy (SMA) and a liquid metal (LM) curvature sensor. While SMA-based actuators are commonly employed in soft robots for various motions, they face challenges such as overheating and long-term degradation if electrically stimulated too quickly. To address this, we integrate a capacitive LM sensor into the soft actuator to measure bending curvature, allowing for a closed-loop control system. The thin and elastic nature of the sensor ensures minimal impact on the actuator's mechanical properties. By incorporating the sensor into a closed-loop "bang-bang" controller, we ensure that the actuator fully relaxes to its natural curvature before the next activation cycle, enabling dynamic adaptation of the activation frequency for continuous, cyclic actuation. Additionally, in cases of slower, low-power actuation, the embedded curvature sensor serves as feedback for achieving partial actuation, limiting the degree of curvature change.

Soft robots exhibit unique potential in bio-inspired robotics, emulating the natural mechanics, deformability, and mobility of soft biological organisms. Legged soft robots, designed for walking on various surfaces and navigating tight spaces, heavily rely on the performance of their soft limb actuators. These actuators must possess both high bending stiffness to support the robot's weight during walking and sufficient mechanical compliance to enable deformation through confined spaces. Achieving this combination of load-bearing stiffness and compliance is essential for robust legged locomotion, and various actuator designs, including pneumatic artificial muscles and hydraulically amplified electrostatic actuators, allow for shape and stiffness tuning.

Among these designs, SMAs, such as nickel-titanium (nitinol), are popular due to their high work density, versatile form factor, and electrically activated capabilities. However, SMA actuators face challenges in operation, particularly at high frequencies, as they require heating and cooling cycles to induce the shape memory phase transition. Rapid reactivation can lead to permanent changes in the nitinol crystal structure. While closed-loop strategies based on electrical resistance and temperature measurements have been proposed, they struggle to accommodate the fast push-off motions required for soft robot locomotion.

To address these challenges, we introduce a sensorized SMA actuator featuring a thermally conductive elastomer embedded with a nitinol wire and a soft capacitive strain gauge. The strain gauge, comprised of microfluidic channels of LM alloy in a soft silicone elastomer, has negligible influence on the actuator's natural stiffness and mechanics. This contrasts with other sensor architectures using conductive filler particles within a stretchable elastomer matrix. The

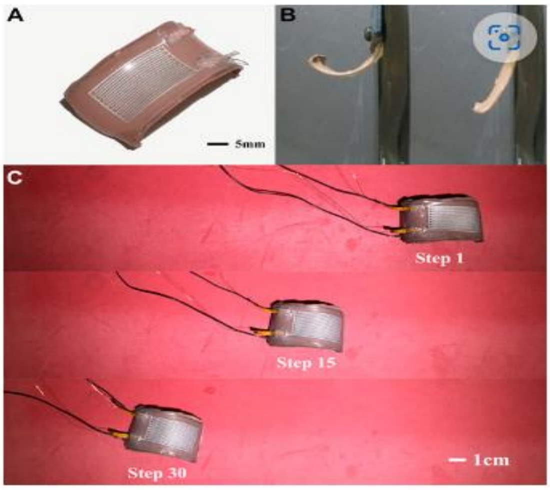


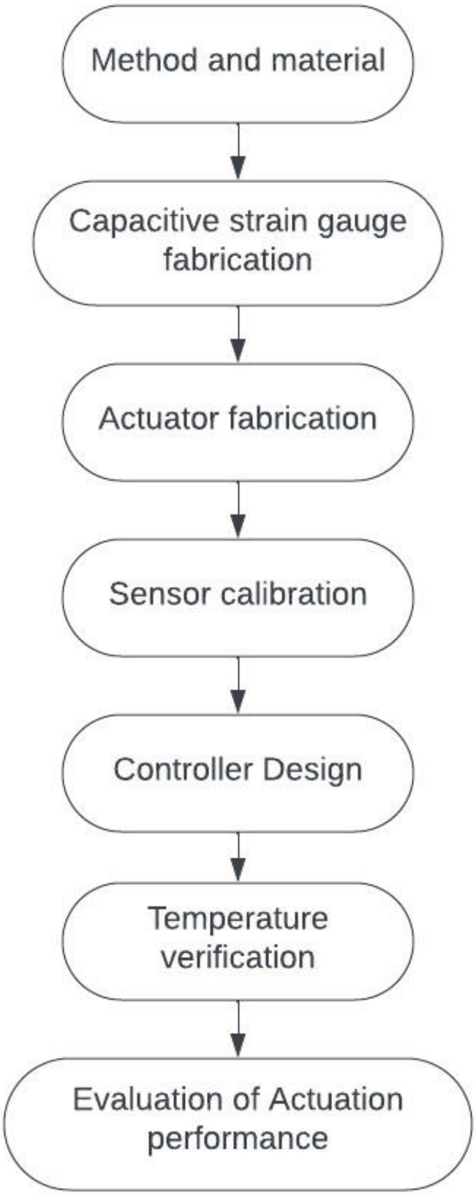
Figure 3.1. (A) Sensorized SMA actuator composed of thermally conductive elastomers, U-shaped SMA wire and LM strain gauge. (B) The relaxed (LEFT) and activated (RIGHT) state of the actuator. (C) Locomotion of single actuator with closed-loop control using sensor feedback.

embedded LM strain gauge allows for continuous, cyclic actuation by tracking limb curvature, and a control scheme ensures the actuator fully recovers to its natural curled compliant shape before the next activation cycle.

The actuator design involves a U-shaped nitinol wire embedded between unstretched and stretched elastomer layers, enabling reversible transformation between an unactuated soft curled shape and an actuated rigid straightened shape. Previous flexural SMA actuators demonstrated untethered soft quadruped locomotion, but without sensors to monitor actuator relaxation. In our approach, the embedded LM strain gauge facilitates real-time tracking of limb curvature, ensuring the actuator's full recovery before the next actuation cycle through a closed-loop control scheme.

Chapter 4: Future Work

As we proposed an idea on which we will work in future. We will be working according to mentioned flowchart:



https://lucid.app/lucidchart/71799ce0-27a6-4b98-bbdb-78adac8855a2/edit?invitationId=inv_5f734c8a-cc01-445f-b1bf-3af79c42a4e2

Conclusion:

In conclusion, SMA based actuators open up new possibilities in robotics by allowing simple, small-scale, and modular implementations of bio-inspired and swarm robotic systems capable of complex collective behaviour using distributed control paradigms. Combining compliant SMA actuation that can mimic organic movement with soft bodies made of elastomers, textiles and gels promises more agile, versatile and fault-tolerant robotic systems that can better handle real-world variability beyond controlled factory settings.

Dozens of research prototypes have already successfully demonstrated the potential across a variety of locomotive gaits and manipulation scenarios. But more work remains to improve cycling lifetime and mechanical properties like torsional actuation capabilities for strength matching applications. Alternate high strain ferromagnetic SMAs may prove better for such uses once production and processing methods mature. Motion planning algorithms also need further development to fully exploit the unique attributes of SMA actuators.

With rising applications from medical devices to wearable robotics and human-assistive devices that require intrinsic safety and robustness, demand for SMA components will likely keep increasing. This will spur advances in manufacturability and embeddability to help transition promising technologies from laboratories towards practical commercial adoption. If creative interdisciplinary solutions can overcome limitations of single SMA actuators via innovative mechanical amplification schemes and composite assemblies, they may find widespread mainstream adoption within the next decade.

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