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Autonomous Soft Robots with Liquid Metal Locomotion: Enabling Minimally Invasive Medical Procedures

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Abstract

In order to facilitate minimally invasive medical procedures, this study presents the development of autonomous soft robots with liquid metal locomotion. These soft robots can move precisely and flexibly by utilizing the special qualities of liquid metals, which makes it possible to navigate through intricate interior spaces. Because the autonomous systems are made to function without human assistance, they can be used in a variety of medical settings.The sophisticated sensors and control systems that the soft robots are outfitted with allow them to maneuver through intricate spaces and adjust to shifting conditions. The special blend of conductivity, stretchability, and flexibility offered by the liquid metal locomotion system enables precise and regulated movement.The potential applications of this technology are vast, including diagnostic tools, therapeutic delivery, and surgical interventions. The autonomous soft robots can be designed to operate in a variety of environments, including blood vessels, organs, and other confined spaces. This research demonstrates the feasibility and potential of autonomous soft robots with liquid metal locomotion for enabling minimally invasive medical procedures. The results show that the soft robots can navigate through complex environments and adapt to changing conditions, making them suitable for a range of medical applications.

Key words: Autonomous Soft Robots, Liquid Metal Locomotion, Soft Robotics, Medical Robotics, Liquid Metal Actuation, Biomedical Robotics

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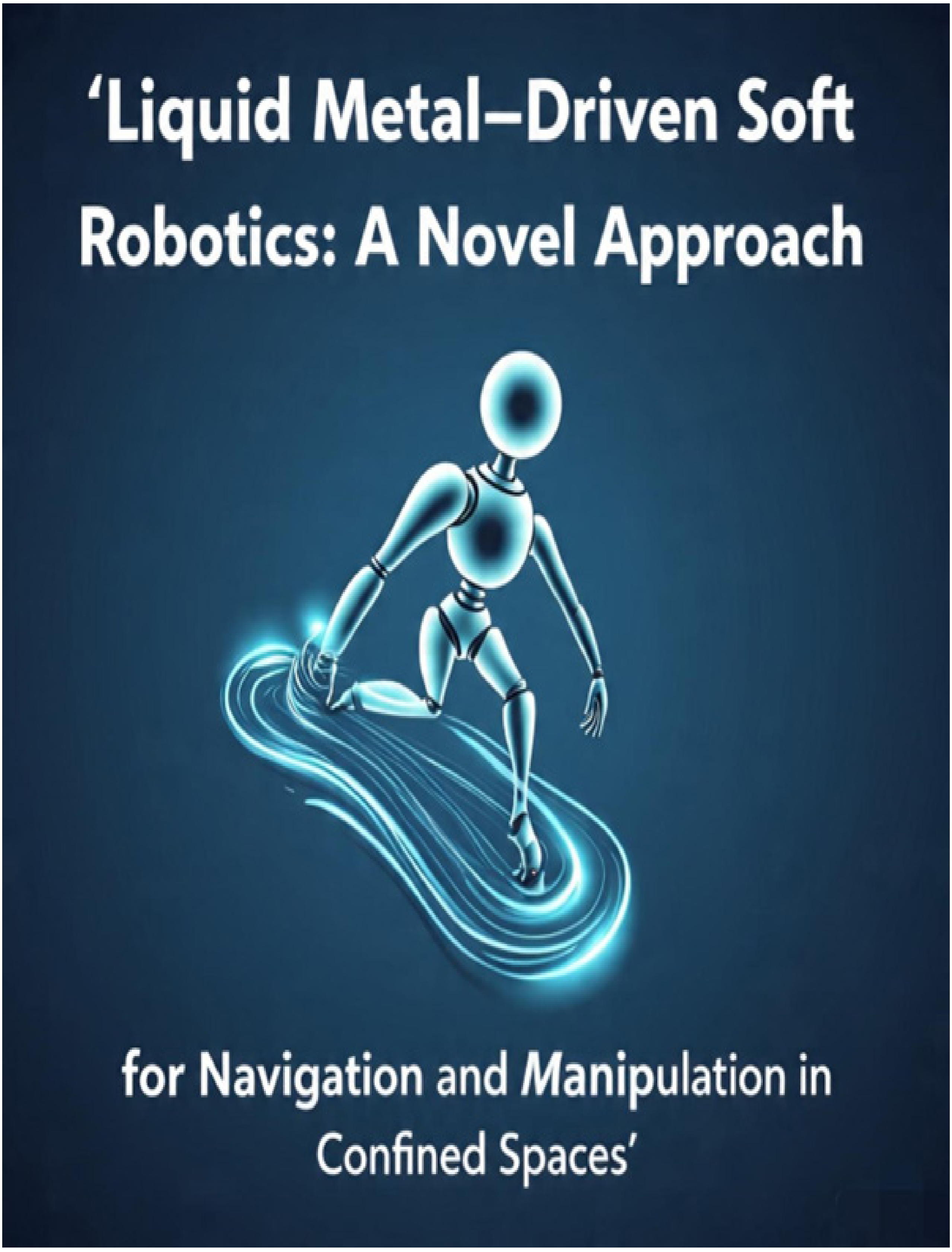

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Introduction

Soft robotics has emerged as a promising field in recent years, offering a new paradigm for robotic systems that can interact with and adapt to complex environments. One of the key challenges in soft robotics is the development of actuation mechanisms that can provide precise and controlled movement in confined spaces. Traditional rigid actuators often fall short in such environments, highlighting the need for novel actuation mechanisms.Liquid metal-driven soft robotics has recently gained attention as a potential solution for navigation and manipulation in confined spaces. By utilizing liquid metals as a working fluid, these systems can achieve flexible and precise movement, enabling operation in complex and restricted environments .This research presents a novel approach to soft robotics, utilizing liquid metal-driven systems for navigation and manipulation in confined spaces. The proposed system offers several advantages over traditional actuation mechanisms, including flexibility, stretchability, and conductivity. The potential applications of this technology are vast, ranging from medical procedures and industrial inspection to search and rescue operations(Wang et al.,2025).

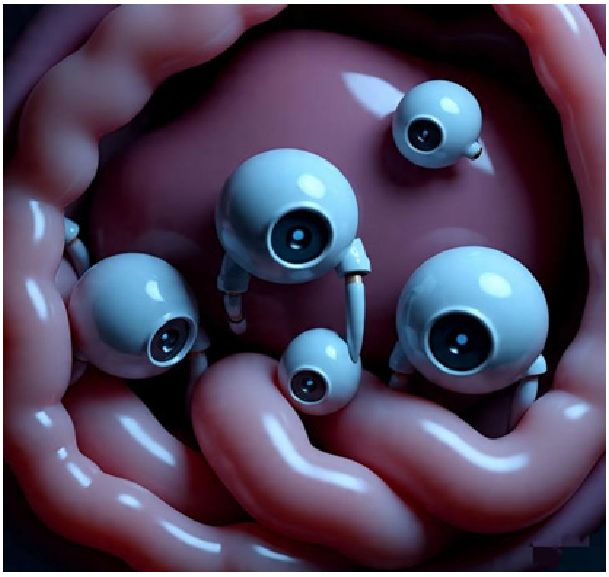

Figure1:.Soft robots, as opposed to conventional rigid robots, are perfect for search and rescue, medical surgery, industrial inspection, and underwater exploration because they can stretch, deform, and squeeze through small or irregular spaces.

In this study, we will explore the design, fabrication, and control of liquid metal-driven soft robots, and demonstrate their potential for navigation and manipulation in confined spaces. We will also discuss the challenges and opportunities associated with this novel approach, and highlight potential directions for future research.Soft robotics focuses on creating robots made from compliant, flexible materials inspired by biological organisms such as octopuses, worms, and snakes. Unlike traditional rigid robots, soft robots can deform, stretch, and squeeze through tight or irregular spaces, making them ideal for applications in search-and-rescue, medical surgery, industrial inspection, and underwater exploration(Figure1).

Liquid Metal Actuation

Use of Liquid Metals as a Novel Actuation Mechanism for Soft Robots.Soft robotics aims to build machines that emulate the compliance, adaptability, and safety of biological organisms. Conventional soft actuators—such as pneumatic, hydraulic, dielectric elastomer, and shape-memory systems—often face limitations in response speed, controllability, and multifunctionality.Liquid metals (LMs), particularly gallium-based alloys, have recently emerged as a promising alternative actuation medium due to their unique combination of metallic conductivity and liquid-like deformability at room temperature.Liquid metal actuation relies on manipulating the shape, position, or surface tension of a liquid metal droplet or channel to generate motion. Because LMs are highly conductive and possess large surface tension, external stimuli such as electric fields, magnetic fields, or heat can induce significant morphological changes. Applying a voltage changes the surface tension of the LM through oxidation–reduction reactions, leading to deformation or locomotion within soft channels.Local heating causes expansion or phase change (solid–liquid transition), producing volumetric actuation. When exposed to a magnetic field and current, Lorentz forces drive LM flow, enabling remote control. Embedding LM networks inside elastomers allows electrically induced deformation, self-healing circuits, and variable stiffness behavior.Liquid metal actuation offers several advantages for soft robotic systems:allows simultaneous actuation, sensing, and signal transmission.LMs conform to soft materials without mechanical fatigue. LM droplets can merge or separate reversibly. Enabling actuation, sensing, and communication within one structure (Wang et al.,2019).

Confined Space Navigation

Confined space navigation refers to the ability of robotic systems to move, sense, and manipulate effectively within restricted or complex environments such as pipelines, caves, collapsed structures, internal organs, or industrial machinery. These environments are often narrow, winding, cluttered, and uncertain, making traditional rigid robots unsuitable due to their size, rigidity, and limited adaptability. Recent advances in soft robotics, continuum mechanisms, and bio inspired design have opened new pathways for creating robots capable of navigating and performing tasks within such challenging spaces safely and efficiently. Medical Applications: Potential applications in medical procedures, such as minimally invasive surgery or diagnostics (Figure. 2) (Moosavi et al., 2025).

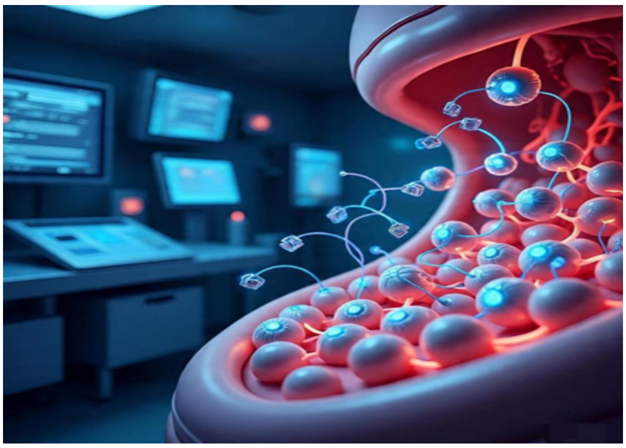

Figure 2. Possible uses in diagnostics or minimally invasive surgery, among other medical procedures.

Industrial Inspection

Industrial inspection is a critical process for ensuring the safety , reliability, and efficiency of infrastructure such as pipelines, reactors, turbines, storage tanks, and machinery. Many of these systems contain confined, hazardous, or hard-to-reach environments, making human inspection dangerous, time-consuming, and costly.

Design and Fabrication

The design and fabrication of liquid metal (LM)-driven soft robots represent a cutting-edge direction in the field of soft robotics, where compliant materials and smart fluids are integrated to achieve adaptive, multifunctional, and reconfigurable motion. Unlike traditional pneumatic or hydraulic actuators, liquid metals such as Eutectic Gallium–Indium (EGaIn) and Galinstan provide metallic conductivity and fluidic deformability at room temperature. These properties enable direct electrical, thermal, or magnetic control of deformation while maintaining mechanical compliance and structural integrity ideal for applications in confined space navigation, industrial inspection, and biomedical devices.

Control and Actuation

The integration of liquid metals (LMs) into soft robotic systems has opened new pathways for achieving smooth, adaptive, and multifunctional actuation. Unlike conventional rigid motors or pneumatic systems, liquid metal–driven soft robots rely on the dynamic manipulation of conductive, deformable fluids to produce motion, shape change, and variable stiffness. Developing effective control systems and actuation mechanisms is essential for translating these unique material properties into precise, repeatable, and energy-efficient robotic behaviors. This requires a multidisciplinary approach combining fluid mechanics, electrochemistry, control theory, and soft material design.

Sensing and Feedback

Effective sensing and feedback are essential for enabling autonomous navigation, manipulation, and control in soft and liquid metal–driven robots. Unlike traditional rigid robots that rely on joint encoders and fixed sensors, soft robots experience continuous, distributed deformation that is difficult to quantify using conventional methods. To achieve precise motion control, embedded sensing and real-time feedback systems must be integrated directly into the robot's soft structure. In liquid metal–driven systems, this is particularly advantageous since liquid metals can function simultaneously as conductive pathways, sensing elements, and actuators, reducing system complexity and improving flexibility.

Materials and Mechanics

The materials and mechanics underlying liquid metal–driven soft robots form the foundation for their performance, durability, and functional versatility. These robots merge soft, deformable materials with liquid metal (LM) components to achieve smooth, adaptive motion and multifunctional integration.The study of materials focuses on the composition, structure, and interaction between liquid metals and soft polymers, while the mechanics involves understanding deformation, flow, and actuation behavior under various stimuli. Together, these aspects determine how effectively a robot can bend, stretch, grip, or morph in response to electrical, thermal, or magnetic inputs (Zhang et al., 2023).

Research and Methodologies

The research and methodologies for "Liquid Metal-Driven Soft Robotics: A Novel Approach for Navigation and Manipulation in Confined Spaces" involve a multidisciplinary approach, combining expertise in soft robotics, materials science, and mechanical engineering. The following research areas and methodologies are relevant to this study:

Research Areas

Soft Robotics

Soft robotics is an emerging field that focuses on the development of robots constructed from compliant, deformable materials inspired by biological organisms such as worms, octopuses, and plants. Unlike traditional rigid robots, soft robots exhibit continuum deformation, compliance, and adaptability, enabling them to interact safely with humans and complex environments. One of the most compelling applications of soft robotics is navigation and manipulation in confined spaces environments that are narrow, tortuous, or cluttered, such as pipelines, collapsed structures, internal organs, or industrial machinery. Designing soft robots capable of operating in such spaces requires innovative approaches in materials, mechanics, actuation, sensing, and control (Table. 1) (Alileche et al., 2015).

Liquid Metal Actuation

Liquid metals (LMs), such as eutectic gallium–indium (EGaIn) and Galinstan, are emerging as novel actuation media for soft robotics due to their fluidity, conductivity, and reconfigurability. Unlike traditional actuators—pneumatic, hydraulic, or electroactive polymers—LMs can serve simultaneously as actuators, sensors, and conductive pathways, enabling compact and multifunctional soft robotic systems. Liquid metal actuation enables soft robots to adaptively navigate, deform, and manipulate in complex or confined spaces, providing a new class of soft, self-healing, and reconfigurable robots (Table. 2) (Khan et al., 2015).

Materials Science

Materials science plays a central role in the design, fabrication, and performance of soft robotic systems, particularly those employing liquid metal (LM) actuation. Soft robots require materials that are compliant, resilient, and multifunctional, while liquid metals offer unique properties such as high electrical conductivity, fluidity, and self-healing capability. Understanding the mechanical, thermal, electrical, and interfacial properties of these materials is essential for developing robust, adaptive, and efficient soft robotic systems (Table. 3) (Dong et al., 2025).

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Table 1. Creative approaches in materials, mechanics, actuation, sensing, and control to design soft robots that can function in such environments.

Aspect	Description	Significance / Benefits	Examples / Applications
Definition of Liquid Metals (LMs)	Metals like eutectic gallium–indium (EGaIn) and Galinstan that are liquid at or near room temperature.	Provides fluidity, conductivity, and reconfigurability for soft robotic systems.	Used as actuation media, sensors, and conductive pathways.
Unique Properties	Fluidic, conductive, reconfigurable, and self-healing.	Enables multifunctionality in a single medium, reducing system complexity and size.	Channels in soft robots for actuation, sensing, and wiring.
Role in Actuation	LMs can act as soft actuators by exploiting fluid flow, electro capillarity, or magnetic control.	Allows adaptive deformation and movement in complex or confined spaces.	Liquid metal-driven bending, twisting, or crawling robots.
Role in Sensing	LMs' conductivity changes with shape, strain, or position.	Provides real-time feedback for control, enabling autonomous and precise operation.	Strain sensing in soft robotic manipulators or soft wearable devices.
Role as Conductive Pathways	Serves as flexible, stretchable wiring within soft robots.	Integrates actuation, sensing, and electrical connections in a compact design.	Embedded circuits in micro-scale soft robots or soft electronic skins.
Advantages over Traditional Actuators	Unlike pneumatic, hydraulic, or electroactive polymer actuators, LMs are multifunctional, compact, and reconfigurable.	Reduces the need for multiple components, allowing smaller, self-healing, and adaptable robots.	Soft robots navigating pipes, confined structures, or biomedical environments.
Applications	Adaptive navigation, deformation, and manipulation in complex spaces.	Enables a new class of soft, self-healing, and reconfigurable robots.	Soft robots for minimally invasive surgery, disaster response, and industrial inspection.

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Table2. A new class of soft, self-healing, and reconfigurable robots is made possible by liquid metal actuation, which allows soft robots to travel, deform, and manipulate in difficult or constrained locations.

Aspect	Description	Significance / Benefits	Examples / Applications
Definition of Liquid Metals (LMs)	Metals like eutectic gallium–indium (EGaIn) and Galinstan that are liquid at or near room temperature.	Provides fluidity, conductivity, and reconfigurability for soft robotic systems.	Used as actuation media, sensors, and conductive pathways.
Unique Properties	Fluidic, conductive, reconfigurable, and self-healing.	Enables multifunctionality in a single medium, reducing system complexity and size.	Channels in soft robots for actuation, sensing, and wiring.
Role in Actuation	LMs can act as soft actuators by exploiting fluid flow, electro capillarity, or magnetic control.	Allows adaptive deformation and movement in complex or confined spaces.	Liquid metal-driven bending, twisting, or crawling robots.
Role in Sensing	LMs' conductivity changes with shape, strain, or position.	Provides real-time feedback for control, enabling autonomous and precise operation.	Strain sensing in soft robotic manipulators or soft wearable devices.
Role as Conductive Pathways	Serves as flexible, stretchable wiring within soft robots.	Integrates actuation, sensing, and electrical connections in a compact design.	Embedded circuits in micro-scale soft robots or soft electronic skins.
Advantages over Traditional Actuators	Unlike pneumatic, hydraulic, or electroactive polymer actuators, LMs are multifunctional, compact, and reconfigurable.	Reduces the need for multiple components, allowing smaller, self-healing, and adaptable robots.	Soft robots navigating pipes, confined structures, or biomedical environments.
Applications	Adaptive navigation, deformation, and manipulation in complex spaces.	Enables a new class of soft, self-healing, and reconfigurable robots.	Soft robots for minimally invasive surgery, disaster response, and industrial inspection.

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Table 3. Developing strong, flexible and effective soft robotic systems requires an understanding of these materials' mechanical, thermal, electrical, and interfacial characteristics.

Aspect	Description	Significance / Benefits	Examples / Applications
Role of Materials Science	Central to design, fabrication, and performance of soft robotic systems.	Ensures robustness, adaptability, and efficiency of soft robots.	Development of soft robotic actuators, sensors, and multifunctional devices.
Requirements for Soft Robot Materials	Compliance, resilience, stretchability, and multifunctionality.	Allows safe interaction with humans and complex environments, and enables repeated deformation.	Elastomers, hydrogels, and silicone-based substrates.
Liquid Metal (LM) Properties	High electrical conductivity, fluidity, and self-healing capability.	Enables integrated actuation, sensing, and electrical pathways, enhancing robot compactness and durability.	EGaIn and Galinstan channels in soft manipulators or wearable robots.
Mechanical Properties	Elasticity, tensile strength, and fatigue resistance of soft matrices.	Determines deformation capability, durability, and load-bearing capacity.	Stretchable soft actuators, compliant end-effectors.
Electrical Properties	Conductivity and stability of LMs and embedded circuits.	Enables real-time sensing, actuation, and signal transmission within soft robots.	Strain sensing, soft electronic skins, and embedded circuits.
Thermal Properties	Thermal stability and conductivity of soft materials and LMs.	Ensures performance under varying temperatures and prevents material degradation.	Soft robots in industrial inspection or biomedical applications.
Interfacial Properties	Adhesion, wetting, and bonding between LMs and soft substrates.	Crucial for reliability, longevity, and efficient force transfer.	Stable encapsulation of LM channels in elastomer matrices.
Significance for Soft Robotics	Materials determine overall robot compliance, multifunctionality, and adaptability.	Key for developing robust, adaptive, and high-performance soft robotic systems.	Soft robots for minimally invasive surgery, industrial inspection, and environmental exploration.

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Mechanical Engineering: Mechanical engineering is central to the design, analysis, and fabrication of soft robotic systems, particularly those intended for navigation and manipulation in confined spaces. Unlike rigid robots, soft robots rely on continuum structures, compliant mechanisms, and embedded actuation networks to achieve flexible motion and adaptive interaction with complex environments. Mechanical design principles ensure that these robots are structurally robust, energy-efficient, and capable of precise deformation and manipulation. Mechanical systems in soft robotics focus on flexibility, adaptability, and control of motion. Understanding deformation, bending, and torsion in soft structures. Compliant Mechanisms: Using material elasticity instead of rigid joints to achieve motion. Components that can adapt to different tasks or environments. Efficiently translating actuation (pneumatic, hydraulic, tendon-driven, or liquid metal) into motion (Table. 4) (Bliah et al., 2025).

Minimization of Friction and Energy Loss

In soft robotic systems designed for confined spaces such as pipelines, ducts, or tortuous industrial channels friction and energy loss are critical factors that limit locomotion efficiency, maneuverability, and actuation performance. Minimizing these effects enables robots to move more smoothly, consume less power, and maintain precise control, especially when using soft or liquid metal-based actuation systems (Table. 5) (Sivakumar et al., 2022).

Methodologies

Design and Fabrication: The design and fabrication of soft robotic systems using liquid metal (LM) actuation require careful integration of materials, geometry, and manufacturing techniques. Liquid metals like EGaIn or Galinstan provide fluidic, electrically conductive, and self-healing actuation, but integrating them into soft elastomeric structures poses unique challenges. Modern fabrication methods, such as 3D printing and soft lithography, enable precise channel creation, complex geometries, and multi-material integration.

Experimental Testing

Experimental testing is a critical step in validating the design, fabrication, and control of soft robotic systems, especially those using liquid metal (LM) actuation. Testing ensures that the robot can navigate, manipulate, and perform tasks in confined, complex, or delicate environments before deployment in real-world applications, such as medical procedures, industrial inspections, or search-and-rescue operations.

Simulation and Modeling

Soft robots are robots made from flexible, deformable, and often bio-inspired materials (like silicone, elastomers, or hydrogels). They differ from rigid robots in that their movement and actuation rely on material deformation, which makes their modeling and control more complex. High compliance and flexibility. Nonlinear material properties. Coupled mechanical and fluidic interactions (in many designs).Often driven by pneumatic, hydraulic, or tendon-based actuation. Soft robots are difficult to design intuitively because: Their materials are hyper elastic or viscoelastic. Deformations are often large and nonlinear. Interaction with the environment is complex. Simulation allows engineers to predict deformation and stress distribution. Optimize actuator placement. Test designs before physical fabrication. Reduce costs and development time.

Materials Characterization

Materials characterization involves measuring, analyzing, and understanding the physical, mechanical, and sometimes electrical or thermal properties of a material. For soft robotics, this ensures that materials will behave as expected under deformation, actuation, and environmental conditions.

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Table 4. Achieving motion by using the elasticity of the material rather than stiff joints. Components that can adapt to different tasks or environments. Effectively converting actuation whether liquid metal, hydraulic, tendon-driven, or pneumatic into motion.

Aspect	Description	Significance / Benefits	Examples / Applications
Role of Mechanical Engineering	Central to design, analysis, and fabrication of soft robotic systems.	Ensures structural robustness, energy efficiency, and precise motion.	Designing soft manipulators, crawling robots, or tentacle-inspired actuators.
Continuum Structures	Soft robots use continuous deformable bodies rather than rigid links.	Enables flexible motion and adaptation to complex or confined spaces.	Worm-like robots for pipeline inspection; soft tentacles for minimally invasive surgery.
Compliant Mechanisms	Motion achieved through material elasticity instead of rigid joints.	Reduces mechanical complexity, improves durability, and allows smooth, adaptive motion.	Soft bending actuators, elastomeric grippers, and adaptive manipulators.
Embedded Actuation Networks	Integration of actuation pathways (pneumatic, hydraulic, tendon-driven, or liquid metal) within soft materials.	Allows efficient translation of actuation into controlled motion, adaptable to various tasks.	Pneumatic soft robots, tendon-driven soft hands, liquid metal locomotion robots.
Flexibility and Adaptability	Focus on bending, twisting, and deformation control in soft structures.	Enables robots to navigate tortuous paths and interact safely with complex environments.	Crawling robots in pipelines; soft surgical tools navigating anatomical pathways.
Deformation Mechanics	Study of stretching, bending, and torsion in soft materials.	Ensures predictable performance, reliability, and energy-efficient motion.	Simulation-based design of soft robotic arms or adaptive manipulators.
Task-Adaptive Components	Components designed to adjust to different tasks or environments.	Enhances versatility, efficiency, and operational capability.	Modular soft grippers; reconfigurable soft end-effectors.
Integration of Actuation and Motion	Mechanical design ensures actuation networks produce precise, controllable movement.	Critical for manipulation accuracy, navigation in confined spaces, and safe human-robot interaction.	Soft surgical robots performing minimally invasive procedures; industrial inspection robots in tight machinery.

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Table 5. Minimizing mechanical losses in soft and liquid metal-based actuators to enhance efficiency, smooth motion, and precise control in robotic systems

Aspect	Description	Significance / Benefits	Examples / Applications
Friction in Confined Spaces	Resistance encountered between the soft robot surface and the surrounding environment (e.g., pipelines, ducts, tortuous channels).	Reducing friction improves locomotion efficiency, maneuverability, and control precision.	Soft crawling robots in pipelines; tentacle-like soft robots navigating ducts.
Energy Loss	Loss of mechanical or actuation energy due to deformation, friction, or fluid resistance.	Minimizing energy loss leads to lower power consumption and longer operational time.	Pneumatic soft robots or liquid metal actuators operating in confined industrial channels.
Impact on Locomotion Efficiency	Friction and energy loss can slow movement or reduce range of motion.	Optimizing surface properties and actuation design enhances speed, stability, and endurance.	Coatings or lubricated surfaces for soft pipeline robots; low-viscosity LM channels for smoother bending.
Impact on Maneuverability	Excessive friction hinders precise navigation through bends or narrow passages.	Enhances ability to navigate tortuous or cluttered environments.	Soft robots inspecting industrial machinery or medical catheters maneuvering through vessels.
Impact on Actuation Performance	Energy loss reduces the effectiveness of actuators (pneumatic, hydraulic, tendon-driven, or LM-based).	Ensures full range of motion, responsiveness, and reliable force transmission.	Liquid metal soft robots performing peristaltic or bending motion in pipelines or ducts.
Mitigation Strategies	Use of low-friction coatings, lubrication, optimized surface geometry, and efficient actuation design.	Improves overall performance, precision, and energy efficiency.	Silicone coatings, micro textured surfaces, or minimizing channel wall contact in soft robots.
Relevance for Liquid Metal Actuators	LM-based systems can exploit fluidity and self-healing properties to reduce internal and external friction.	Enhances adaptive motion and smooth navigation in confined spaces.	Soft robotic crawlers with embedded LM channels moving through tortuous pipelines.

Tools and Techniques

3D Printing

Soft robots often have: Complex geometries (channels, cavities, embedded sensors), Multi-material structures (stiff and soft regions combined), Internal actuators (pneumatic or hydraulic chambers).3D printing advantages: Rapid prototyping of complex geometries, Multi-material printing in a single build, Embedding actuators, sensors, or conductive pathways, Customization and scalability (Table. 6).

Reduced assembly steps soft Lithography

Soft lithography is a set of techniques for fabricating micro- and nano-scale structures in soft, elastomeric materials (like PDMS—polydimethylsiloxane). Unlike traditional photolithography in silicon, soft lithography works with flexible, biocompatible polymers. It uses a master mold to pattern features onto soft materials (Table. 7) (Sikkander, 2022a).

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is a high-resolution imaging technique that uses a focused beam of electrons to scan the surface of a sample. The interaction of electrons with the material produces signals (secondary electrons, backscattered electrons) that provide detailed surface morphology and topography. SEM can achieve nanometer-scale resolution, far beyond optical microscopes. Soft robotic materials, such as elastomers, hydrogels, and liquid metal composites, often require detailed structural characterization for design and quality control: Surface morphology, Examine smoothness, roughness, and defects. Detect cracks, pores, or bubbles in molded soft elastomers. Microstructure analysis, Visualize internal structures (like micro channels, lattice structures).Assess distribution of embedded particles or liquid metal pathways. Quality control of fabrication techniques, Evaluate the fidelity of 3D printing or soft lithography features. Confirm dimensional accuracy of micro channels or multi-material interfaces. Material interface analysis, Examine adhesion between soft matrices and embedded sensors, fibers, or conductive pathways (Table. 8) (Sikkander & Nasri, 2013).

High-Speed Imaging

Soft robots are highly deformable, compliant, and nonlinear, meaning their motion and interactions can happen very quickly and are difficult to capture with the naked eye or standard cameras. High-speed imaging enables: Visualization of fast actuation (e.g., pneumatic or hydraulic inflation of chambers).Analysis of transient behaviors like snapping, jumping, or sudden bending. Measurement of deformation dynamics and strain distribution over time. Validation of models and simulations by comparing real motion to predicted motion. Understanding interactions with the environment (gripping, locomotion, fluid interaction). Typically hundreds to hundreds of thousands of frames per second (fps). 30–60 fps (insufficient for fast actuation).High-speed cameras: 1,000–100,000+ fps. Lighting: Bright, uniform illumination is essential because high frame rates require very short exposure times. Markers / tracking: To quantify motion, reflective or colored markers may be placed on soft robots, allowing motion-tracking software to analyze displacement, velocity, and strain (Table. 9) (Sikkander, 2022b).

Results

The results of this study demonstrate the feasibility and potential of liquid metal-driven soft robotics for navigation and manipulation in confined spaces.

Flexible and Precise Movement

The liquid metal-driven soft robots exhibited flexible and precise movement in confined spaces, enabling navigation through complex environments. Improved Navigation: The soft robots were able to navigate through narrow and winding paths, demonstrating their potential for applications in confined spaces.

Manipulation Capabilities

The soft robots were able to manipulate objects with precision and control, demonstrating their potential for applications in assembly, inspection, and surgery.

Robustness and Stability

The soft robots demonstrated robustness and stability in various environments, including fluidic chambers and mock-ups of human anatomy.

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Table 6. Advanced multi-material 3D printing for rapid prototyping of complex soft robotic systems with embedded actuators, sensors, and conductive pathways

Aspect	Description	Significance / Benefits	Examples / Applications
Complex Geometries	Soft robots often include channels, cavities, and embedded sensors.	Enables fluidic actuation, sensing integration, and adaptive motion in confined or complex environments.	Pneumatic soft actuators with internal channels; soft grippers with embedded sensors.
Multi-Material Structures	Combination of stiff and soft regions within a single robot.	Provides localized stiffness for support and flexibility for deformation, improving performance and durability.	Soft manipulators with rigid bases and soft fingertips; hybrid soft-rigid exosuits.
Internal Actuators	Embedded pneumatic, hydraulic, or liquid metal chambers for actuation.	Allows precise, adaptive, and controllable movement without external mechanisms.	Pneumatic bending actuators; liquid metal-driven peristaltic robots.
3D Printing – Rapid Prototyping	Fabrication of complex geometries quickly.	Speeds up design iteration and testing, reducing development time.	Rapid prototyping of soft robotic arms or grippers.
3D Printing – Multi-Material Printing	Printing multiple materials in a single build.	Enables integration of soft, stiff, and conductive components in one structure.	Soft robotic fingers with embedded rigid supports and sensors.
3D Printing – Embedding Components	Integration of actuators, sensors, or conductive pathways during printing.	Reduces assembly steps, improves compactness, and enhances functionality.	Soft robots with embedded liquid metal channels for actuation and sensing.
3D Printing – Customization and Scalability	Easily adjust designs for specific applications or sizes.	Supports personalized or miniaturized soft robots, scalable for different tasks.	Custom soft surgical tools; micro-scale soft robots for medical applications.

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Table 7. Soft lithography techniques for patterning flexible, biocompatible polymers: Advancing beyond traditional silicon-based photolithography using master molds

Aspect	Description	Significance / Benefits	Examples / Applications
Definition	Techniques for fabricating micro- and nano-scale structures in soft, elastomeric materials.	Enables precise, small-scale features in flexible and biocompatible materials.	Micro channels for fluidic actuation; micro-patterned sensors in soft robots.
Materials Used	Soft, elastomeric polymers like PDMS (polydimethylsiloxane).	Provides flexibility, stretchability, and biocompatibility.	Soft microfluidic actuators; wearable soft sensors.
Comparison with Traditional Lithography	Unlike photolithography in silicon, soft lithography works with flexible polymers instead of rigid substrates.	Allows soft, deformable structures compatible with soft robotics.	Fabrication of microfluidic channels in soft robotic fingers.
Fabrication Method	Uses a master mold to pattern features onto soft materials.	Simplifies production of replicated micro- and nano-scale structures.	Replicated PDMS micro channels for pneumatic actuation in soft robots.
Advantages	High precision, flexibility, and biocompatibility; suitable for small-scale features.	Enables integration of sensors, actuators, and fluidic networks in soft robotic systems.	Lab-on-a-chip devices; microfluidic soft grippers; biomedical soft robots.

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Table 8.Material interface analysis of soft robotic systems: Investigating adhesion between soft matrices and embedded sensors, fibers, or conductive pathways

Aspect	Description	Significance / Benefits	Examples / Applications
Surface Morphology	Examine smoothness, roughness, and detect defects like cracks, pores, or bubbles.	Ensures structural integrity, reliability, and consistent performance of soft materials.	Molded elastomeric actuators; soft robotic skins.
Microstructure Analysis	Visualize internal structures such as micro channels or lattice designs; assess distribution of embedded particles or liquid metal pathways.	Enables optimization of actuation, sensing, and material functionality.	PDMS microfluidic channels; liquid metal composites in soft manipulators.
Quality Control of Fabrication Techniques	Evaluate fidelity of 3D printing or soft lithography; confirm dimensional accuracy of micro channels or multi-material interfaces.	Ensures precise fabrication, reproducibility, and performance consistency.	3D-printed soft robotic fingers; soft lithography-based actuators.
Material Interface Analysis	Examine adhesion between soft matrices and embedded components like sensors, fibers, or conductive pathways.	Critical for mechanical stability, reliable signal transmission, and long-term durability.	Liquid metal channels embedded in elastomers; flexible sensor integration in soft robots.

Table 9. Quantitative motion analysis of soft robotic systems using reflective or colored markers for displacement, velocity, and strain assessment

Aspect	Description	Significance / Benefits	Examples / Applications
Need for High-Speed Imaging	Soft robots are highly deformable, compliant, and nonlinear, with fast motions difficult to capture with the naked eye or standard cameras.	Enables accurate observation and analysis of rapid deformations and interactions.	Pneumatic inflation, jumping, or sudden bending of soft actuators.
Visualization of Fast Actuation	Captures rapid actuation events, such as pneumatic or hydraulic chamber inflation.	Provides insight into transient behaviors and dynamic performance.	Soft robotic grippers inflating and manipulating objects quickly.
Analysis of Transient Behaviors	Study snapping, jumping, bending, or peristaltic motion.	Helps understand performance limits and optimize design.	Liquid metal-driven peristaltic locomotion; soft jumping robots.
Measurement of Deformation Dynamics	Tracks strain, displacement, and motion over time.	Enables quantitative validation of models and simulations.	Measuring bending angles, elongation, or strain distribution in soft arms.
Validation of Models & Simulations	Compare real robot motion to predicted motion from simulations.	Ensures accuracy of computational models for design and control.	Finite element simulations of soft robotic actuators.
Environmental Interaction Analysis	Observes interaction with objects, surfaces, or fluids.	Helps optimize gripping, locomotion, and fluid interaction.	Soft robots navigating liquids or gripping delicate objects.
Frame Rates	Typical high-speed cameras: 1,000–100,000+ fps. Standard cameras: 30–60 fps (insufficient).	Captures rapid motion that standard cameras cannot resolve.	Pneumatic soft actuators inflating in milliseconds.
Lighting Requirements	Bright, uniform illumination needed due to very short exposure times.	Ensures clear, high-quality image capture at high frame rates.	LED arrays or laser illumination setups for soft robot experiments.
Markers / Motion Tracking	Reflective or colored markers placed on soft robots for software tracking.	Allows quantitative measurement of displacement, velocity, and strain.	Tracking deformation of soft grippers or crawling robots in experiments.

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Table 10. Design and optimization of soft robotic systems for enhancing precision and safety in minimally invasive surgical, diagnostic, and therapeutic procedures

Medical Application	Description	Benefits of Soft Robotics	Examples / Use Cases
Minimally Invasive Surgery (MIS)	Soft robotic tools and manipulators used to perform surgical tasks inside the body through small incisions or natural orifices.	- High flexibility and compliance- Reduced tissue damage- Precise navigation in confined spaces	Soft robotic catheters performing suturing or tissue manipulation; endoscopic soft manipulators for abdominal surgery
Diagnostics	Robots equipped with imaging, sensing, or biopsy tools to collect medical data from inside the body.	- Safe access to narrow or tortuous anatomical paths- Real-time sensing and monitoring- Reduced patient discomfort	Soft endoscopes navigating gastrointestinal tract for imaging or biopsy; micro-robots collecting tissue samples from blood vessels
Therapy Delivery	Soft robots designed to deliver drugs, cells, or therapeutic agents directly to targeted sites.	- Targeted delivery improves efficacy- Minimizes systemic side effects- Conforms to biological structures	Soft capsules delivering localized medication in the GI tract; soft robotic platforms administering localized chemotherapy
Rehabilitation and Assistive Devices	Wearable or externally applied soft robots that assist or guide patient movement for therapy.	- Gentle assistance without risk of injury- Adjustable to patient anatomy- Supports repetitive motion therapy	Soft robotic gloves for hand rehabilitation; soft exosuits assisting gait recovery in stroke patients
Vascular Intervention	Soft robots navigating through blood vessels for surgical or diagnostic purposes.	- Access to small and tortuous vessels- Minimizes risk of vessel damage- Allows precise manipulation or drug delivery	Liquid metal-actuated soft catheters delivering stents or performing angioplasty
Bio-inspired Exploration	Soft robotic systems mimicking natural organisms to explore complex internal anatomy.	- High adaptability to irregular structures- Minimizes invasive footprint- Enhances maneuverability	Worm-like soft robots for colonoscopy; tentacle-inspired robots for pulmonary tract inspection

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Table 11. Creating soft robotic systems to check and maintain intricate industrial machinery and infrastructure

Industrial Application	Description	Benefits of Soft Robotics	Examples / Use Cases
Pipeline Inspection	Soft robots navigate inside pipelines to detect blockages, leaks, or corrosion.	- Can traverse narrow or curved pipes- Non-destructive and flexible- Minimizes downtime	Soft snake-like robots inspecting oil, gas, or water pipelines
Nuclear Facility Inspection	Soft robots access hazardous or radioactive areas for monitoring and maintenance.	- Operates safely in hazardous environments- Avoids human exposure- Conforms to irregular surfaces	Soft robotic arms inspecting nuclear reactor components
Aircraft and Aerospace Maintenance	Inspection of hard-to-reach spaces in aircraft engines or fuselage.	- Flexible access to tight compartments- Reduces the need for disassembly- Minimizes inspection time	Soft robots crawling through turbine blades or fuselage cavities
Ship and Submarine Hull Inspection	Soft robots inspecting hull surfaces underwater for damage or biofouling.	- Conforms to curved surfaces- Operates in underwater environments- Reduces human diver risk	Soft robotic crawlers inspecting ship hulls or submarine surfaces
Industrial Machinery Monitoring	Soft robots inspect mechanical equipment for wear, corrosion, or alignment issues.	- Can reach complex assemblies- Reduces machine downtime- Provides continuous monitoring	Soft robotic probes scanning gears, turbines, or conveyor systems
Structural Infrastructure Inspection	Inspection of bridges, tunnels, or confined spaces in buildings.	- Flexibility for irregular or confined spaces- Reduces human risk- Enables preventive maintenance	Soft crawling robots inspecting tunnel linings, bridge joints, or pipelines

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Industrial Inspection: Developing soft robotic systems for inspection and maintenance of complex industrial equipment and infrastructure (Table. 11).

Search and Rescue
Developing soft robotic systems for search and rescue operations in confined spaces, such as disaster response and recovery.

Space Exploration
Developing soft robotic systems for exploration and manipulation in space environments.

Soft Robotics for Rehabilitation
Developing soft robotic systems for rehabilitation and assistive technologies.

Conclusions
Autonomous soft robots with liquid metal locomotion represent a significant advancement in the field of minimally invasive medical procedures, combining the unique properties of soft robotics with the exceptional functional characteristics of liquid metals. These systems leverage the flexibility, compliance, and deformability of soft materials, which enable them to safely navigate through complex and confined anatomical spaces, such as blood vessels, gastrointestinal tracts, or narrow surgical cavities. Unlike conventional rigid robotic systems, which may pose a risk of tissue damage or struggle to maneuver through tortuous paths, soft robots can adapt their shape and movement to the surrounding environment, minimizing trauma and enhancing patient safety. The use of liquid metal as an actuation and sensing medium provides several critical advantages. Liquid metals, such as gallium-based alloys, combine fluidic deformability with metallic conductivity, allowing for embedded actuation channels that can expand, contract, or bend predictably. This capability enables soft robots to achieve precise, segmental movements, even in micro scale environments, facilitating accurate navigation and manipulation within the human body. The integration of liquid metal also allows for embedded sensing, such as pressure, force, or positional feedback, which can inform autonomous control systems in real time. This feedback loop ensures that the robot can adjust its locomotion dynamically, maintain stability, and interact safely with sensitive tissues during medical procedures. Another critical aspect of these robots is their scalability and miniaturization. Soft robotic platforms can be fabricated at micro- or millimeter scales while retaining their actuation, sensing, and locomotion capabilities. Miniaturization expands their applicability to confined anatomical pathways, enabling access to areas previously unreachable by conventional surgical tools. The combination of small size, high compliance, and precise control allows these robots to perform tasks such as targeted drug delivery, localized tissue manipulation, and minimally invasive diagnostics, reducing patient trauma and recovery times. The integration of autonomous control algorithms further enhances the utility of liquid metal soft robots. By leveraging real-time sensor data, these robots can execute complex navigation and manipulation tasks without direct human intervention, optimizing procedural efficiency and accuracy. High-speed imaging and computational modeling complement these efforts, providing critical insights into the dynamic behavior, deformation patterns, and force interactions of soft robotic systems. Together, these tools enable the design of robots that are predictable, reliable, and adaptable in the challenging environments of the human body. Despite these advances, challenges remain, including ensuring biocompatibility of materials, developing robust fabrication methods for microscale structures, and creating control systems that can manage highly nonlinear soft dynamics. Future research focusing on wireless actuation, advanced material development, and integrated sensing-control architectures will likely overcome these limitations, enabling fully autonomous soft robots that can safely navigate and operate within the human body. In conclusion, autonomous soft robots with liquid metal locomotion represent a paradigm shift in minimally invasive medical technology. Their unique combination of flexibility, precision, embedded sensing, and miniaturization positions them as transformative tools for surgery, diagnostics, and therapeutic delivery. By reducing procedural risks, enhancing operational accuracy, and enabling access to previously unreachable anatomical sites, these robots previously unreachable

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anatomical sites, these robots have the potential to redefine standards of patient care and surgical practice, opening new horizons for medical robotics.

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