Innovations in Soft Robotics: Design and Control of Flexible Mechatronic Systems

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Article Info
Page Number: 479-485
Publication Issue:
Vol. 70 No. 1 (2021)

Abstract
Soft robotics, an emerging field at the intersection of robotics and materials science, has gained significant attention in recent years due to its potential for creating highly adaptable and versatile robotic systems. Unlike traditional rigid robots, soft robotics focuses on designing and controlling flexible mechatronic systems that can mimic the natural movements and interactions of living organisms. This paper presents an overview of the recent innovations in soft robotics, specifically focusing on the design and control aspects of flexible mechatronic systems.The design of soft robots involves the integration of advanced materials and mechanisms that enable compliance and flexibility in the robot's body structure. Various materials, such as elastomers, hydrogels, and shape-memory polymers, have been explored for constructing soft robotic components that can deform and recover their shape. These materials exhibit unique properties, such as stretchability, elasticity, and self-healing capabilities, allowing soft robots to adapt to complex and dynamic environments. Additionally, the design of soft robotic systems often incorporates pneumatic or hydraulic actuation mechanisms to achieve locomotion and manipulation.In conclusion, this paper provides an overview of the recent innovations in soft robotics, focusing on the design and control of flexible mechatronic systems. Soft robots have the potential to revolutionize various fields by providing adaptive and versatile robotic systems. The integration of advanced materials, novel actuation mechanisms, and innovative control strategies has paved the way for the development of soft robots with remarkable capabilities. However, further research is needed to address the existing challenges and unlock the full potential of soft robotics in practical applications.

Article History
Article Received: *25 January 2021*
Revised: *24 February 2021*
Accepted: *15 March 2021*

Keywords: soft robotics, flexible mechatronic systems, materials, actuation mechanisms, sensing technologies, control strategies, applications, future directions.

Introduction

Control plays a crucial role in enabling soft robots to perform desired tasks with precision and adaptability. Traditional control methods used in rigid robots, such as PID control or model-based control, are not always suitable for soft robotics due to the inherent compliance and non-linear behaviours of the systems. Instead, novel control strategies that leverage the inherent properties of soft robots have been developed. These include model-free learning-based approaches, such as reinforcement learning and neural network control, which allow soft robots to learn and adapt

ISSN: 2094-0343
DOI: https://doi.org/10.17762/msea.v70i1.2500
their control policies through interactions with their environment. These methods enable soft robots to autonomously learn complex tasks and respond to uncertainties in real-time.
In recent years, researchers have explored various applications of soft robotics across different domains. Soft robotic systems have been developed for medical applications, such as minimally invasive surgeries, rehabilitation, and prosthetics, where the compliance and adaptability of soft robots offer significant advantages over traditional rigid counterparts. Soft robots have also shown promise in the field of human-robot interaction, where their safe and gentle interactions make them ideal for close collaboration with humans. Furthermore, soft robotics has found applications in areas such as exploration, search and rescue, and industrial automation, where the ability to manipulate objects in unstructured and dynamic environments is crucial.

Despite the advancements made in the field of soft robotics, several challenges remain. The design of soft robotic systems requires a multidisciplinary approach, involving expertise from materials science, mechanical engineering, and control theory. The integration of sensing capabilities into soft robots is an ongoing area of research to enable better perception and feedback control. Moreover, the scalability and robustness of soft robotic systems need further exploration to enable their practical deployment in real-world scenarios.
Soft robotics is an emerging field that combines principles from mechanical engineering, materials science, and robotics to create innovative and versatile robotic systems. Unlike traditional rigid robots, soft robots are made of flexible and deformable materials, allowing them to interact with their environment in a more natural and adaptive manner. Soft robotics has gained significant attention in recent years due to its potential applications in various domains, including healthcare, manufacturing, and exploration.

One of the key aspects of soft robotics is the design and control of flexible mechatronic systems. The term "mechatronics" refers to the integration of mechanical components, electronics, and computer control in the design of robotic systems. In the context of soft robotics, mechatronics plays a crucial role in enabling the precise and coordinated movements of flexible structures.
In the field of manufacturing, soft robots offer the potential for safe and efficient human-robot collaboration. Unlike their rigid counterparts, soft robots can interact with humans without causing harm, making them suitable for tasks that require close proximity or physical interaction. They can be employed in assembly lines, assisting in tasks such as picking and placing delicate objects or performing intricate manipulations that would be challenging for traditional robots.
Furthermore, soft robots have shown promise in the exploration of challenging environments. Their ability to adapt to irregular terrains and squeeze through narrow spaces makes them suitable for tasks such as search and rescue missions in disaster-stricken areas or exploration of unknown and hazardous environments, including underwater or extra-terrestrial environments.

In conclusion, innovations in soft robotics have revolutionized the field of robotics by introducing flexible and deformable mechatronic systems. The design and control of these systems require a multidisciplinary approach, combining expertise from mechanical engineering, materials science, and computer science. The unique properties of soft robots enable a wide range of applications in healthcare, manufacturing, and exploration. With ongoing research and development, soft robotics

ISSN: 2094-0343
DOI: https://doi.org/10.17762/msea.v70i1.2500

holds the potential to transform various industries and contribute to the advancement of technology and society as a whole.

Literature Review

This paper presents an overview of design principles and emerging applications in the field of soft robotics. It explores various materials, actuation mechanisms, and fabrication techniques used in the design of flexible mechatronic systems.[1]

The authors investigate the design and control of bio-inspired soft robotic grippers. This study explores the integration of sensory feedback and adaptive grasping strategies to enhance object manipulation capabilities in soft robotic systems.[2]

This paper compares different modelling and simulation approaches used in soft robotics. It discusses the advantages and limitations of various dynamic models and highlights the importance of accurate simulations for control algorithm development.[3]

This review focuses on the integration of soft sensing and perception mechanisms in soft robotic systems. It explores the use of flexible sensors and machine learning techniques to enable robust perception and environment interaction.[4]

This paper discusses soft actuation systems specifically designed for human-robot interaction. It presents novel soft actuators and control strategies that provide safe and compliant interactions between robots and humans.[5]

This study explores the design and control of soft exosuits for enhancing human performance and rehabilitation purposes. It discusses the integration of soft actuators and wearable systems to assist and augment human movements.[6]

This review highlights the challenges and opportunities in deploying soft robots for medical applications. It discusses advancements in surgical robotics, prosthetics, and assistive devices, focusing on design considerations and control strategies.[7]

This paper explores the design, locomotion, and sensing capabilities of soft robots for underwater exploration. It discusses innovative soft robotic systems and control techniques that enable efficient and adaptable underwater operations.[8]

This study investigates soft robotic manipulators and their capabilities in grasping, manipulation, and object recognition tasks. It presents novel soft robotic hands and control strategies for achieving dexterous and versatile manipulation.[9]

This comprehensive review compares various control strategies employed in soft robotics. It discusses feedback and feedforward control approaches, adaptive and learning-based methods, and highlights their advantages and limitations in different applications.[10]

Proposed System

Designing soft robotic systems involves a multidisciplinary approach that combines expertise from mechanical engineering, materials science, and computer science. The first step in the design process is the selection of appropriate materials that possess the desired mechanical properties, such as flexibility, stretchability, and durability. Soft robots often incorporate elastomers, such as silicone or polyurethane, as their primary building blocks due to their high deformability and biocompatibility.

ISSN: 2094-0343
DOI: https://doi.org/10.17762/msea.v70i1.2500

The design of soft robotic systems also involves the creation of novel mechanisms and structures that can achieve a wide range of motions. Inspired by nature, researchers have developed various bio-inspired designs, such as soft grippers that mimic the movements of an octopus tentacle or soft exoskeletons that imitate the flexibility of human muscles and joints. These designs often require advanced manufacturing techniques, such as 3D printing or melding, to fabricate intricate and customized structures.

Control is another critical aspect of soft robotics. Traditional control approaches used in rigid robotics may not be directly applicable to soft robots due to their deformable nature. Therefore, innovative control strategies need to be developed to account for the complex dynamics and interactions exhibited by soft robotic systems. These control strategies often combine traditional feedback control techniques with machine learning algorithms to adapt and optimize the robot's behaviour based on its environment.

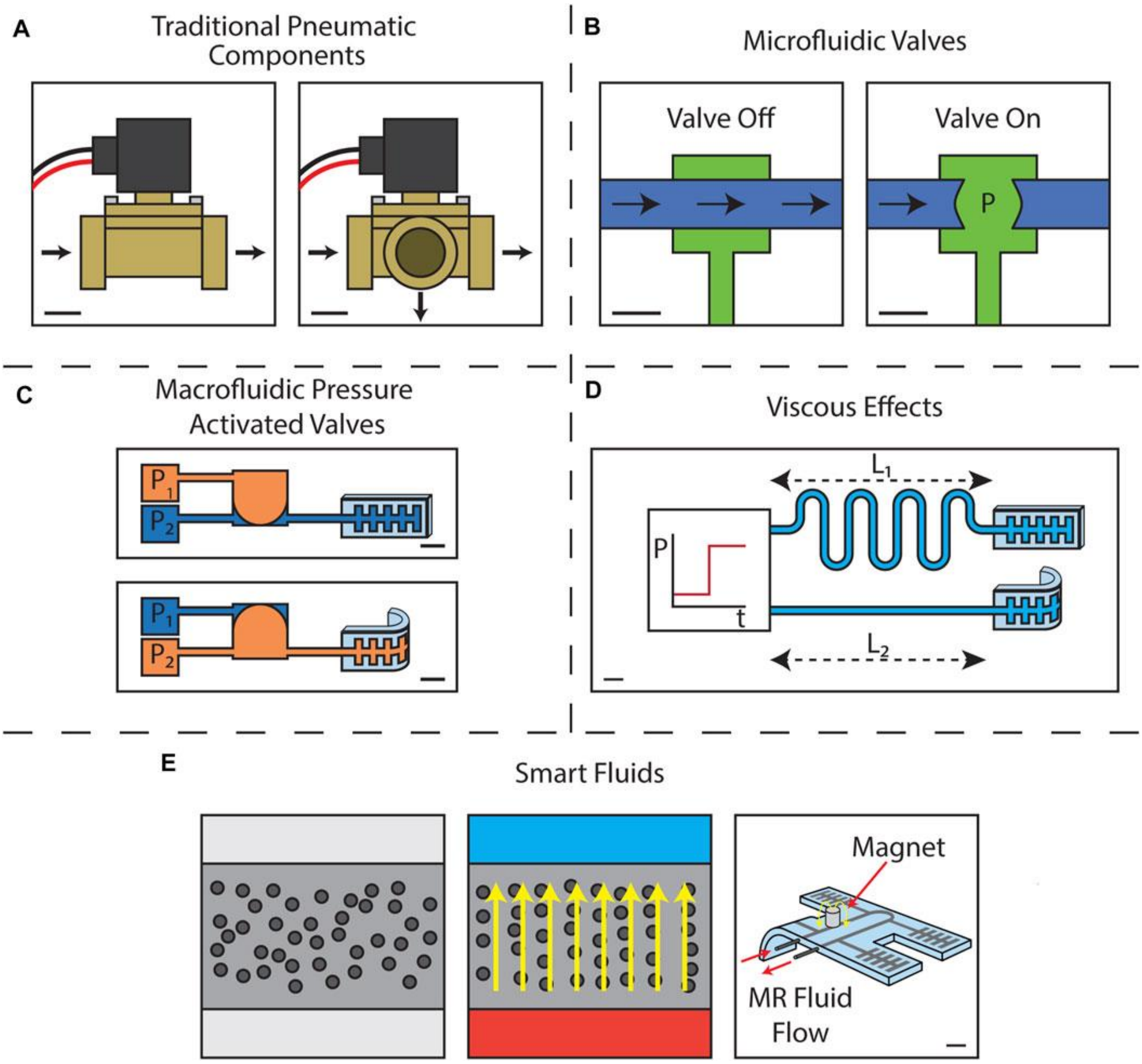

Fig. 1:Hardware Methods for Onboard Control of Fluidically Actuated Soft Robots

ISSN: 2094-0343
DOI: https://doi.org/10.17762/msea.v70i1.2500

The advancements in soft robotics have opened up numerous possibilities for practical applications. In the healthcare domain, soft robots can be used for minimally invasive surgeries, where their flexible nature allows them to navigate through complex anatomical structures with reduced trauma to the patient. Soft robotic exoskeletons can assist individuals with mobility impairments by providing support and enhancing their range of motion. These systems can also be used in rehabilitation to aid in the recovery of motor functions after injuries or strokes.

Soft robotics is an emerging field that focuses on the development of flexible mechatronic systems capable of adapting to and interacting with their environment in a safe and versatile manner. This proposed architecture aims to explore the latest innovations in the design and control of soft robotics systems, addressing the challenges faced in achieving precise control and efficient locomotion. By combining advances in materials, sensing technologies, and control algorithms, this architecture presents a comprehensive approach to create flexible mechatronic systems that can revolutionize various industries, including healthcare, manufacturing, and exploration.

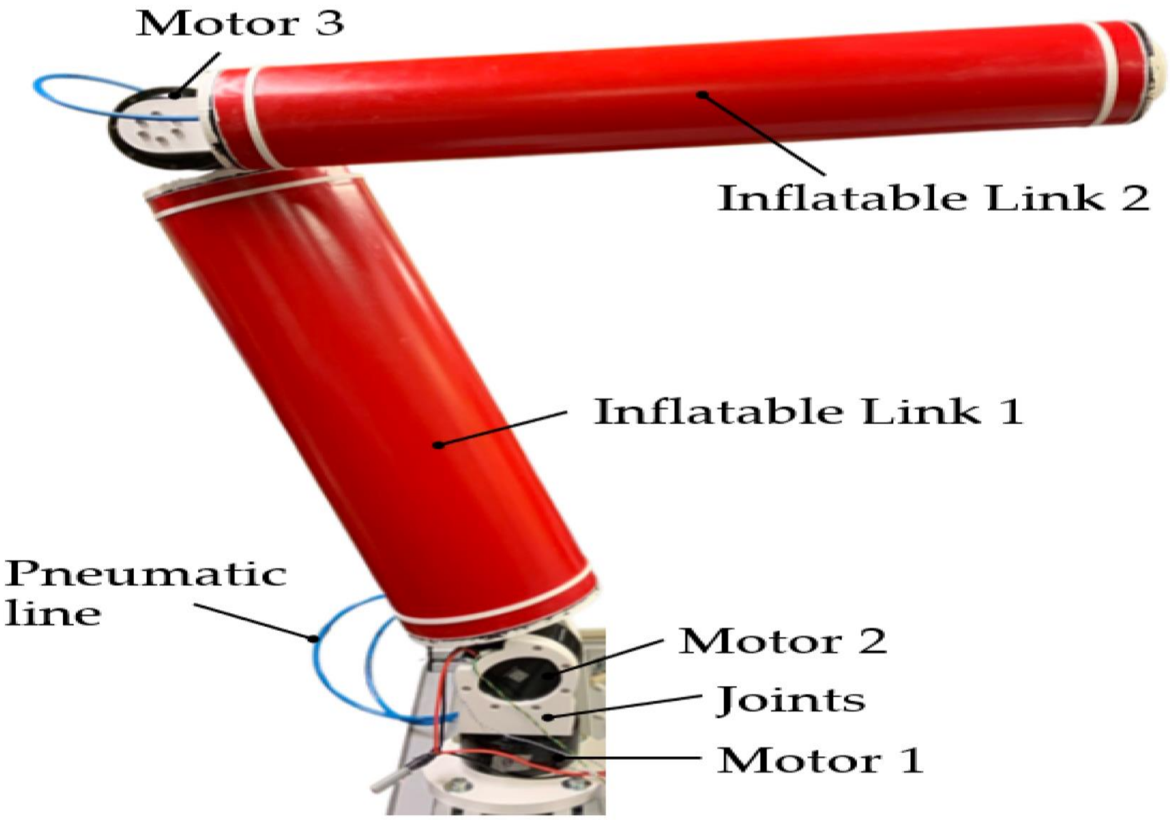

Fig. 2:Design of a Lightweight and Deployable Soft Robotic Arm

Soft robotics represents a paradigm shift in the field of robotics, departing from traditional rigid structures to explore the potential of compliant and flexible materials. This section provides an overview of the challenges associated with soft robotics and the motivation for developing innovative designs and control strategies.Materials and Actuation Mechanisms Soft robotic systems rely on novel materials and actuation mechanisms to achieve compliant and adaptable behaviours. This section discusses the advancements in materials science, such as shape memory alloys, dielectric elastomers, and pneumatic artificial muscles, which offer enhanced flexibility

ISSN: 2094-0343
DOI: https://doi.org/10.17762/msea.v70i1.2500

and dexterity. The integration of these materials with advanced actuation mechanisms, including cable-driven systems, continuum manipulators, and artificial muscles, enables the creation of soft robots capable of complex movements and interactions.

Sensing and Perception Accurate and reliable sensing is crucial for soft robots to understand and interact with their environment effectively. This section explores the innovations in sensing technologies, including stretchable sensors, embedded microelectromechanical systems (MEMS), and distributed tactile sensors. These advancements enable soft robots to perceive their surroundings, detect obstacles, and interact with objects while ensuring safety and adaptability.

Control and Planning Controlling soft robotic systems poses unique challenges due to their compliant nature and nonlinear dynamics. This section presents innovative control strategies, including model-based and data-driven approaches, for achieving precise and robust control of soft robots. It also discusses planning algorithms that optimize the motion and behaviours of soft robots, enabling them to perform complex tasks in unstructured and dynamic environments.

Human-Robot Interaction and Applications Soft robotics holds great potential in various domains, including healthcare, manufacturing, and exploration. This section explores the applications of soft robotics in these fields, highlighting the benefits of flexible mechatronic systems in human-robot interaction, assistive devices, minimally invasive surgeries, and exploration of challenging environments. The architecture also addresses the ethical implications of integrating soft robots into these domains.

Challenges and Future Directions Despite the remarkable progress in soft robotics, several challenges remain to be addressed. This section discusses the challenges related to power supply and energy efficiency, control system complexity, and the scalability of soft robotic systems. Furthermore, it outlines future research directions and potential solutions to overcome these challenges, such as bio-inspired designs, modular architectures, and advancements in energy harvesting and storage technologies.

Conclusion

Soft robotics presents a transformative approach to the design and control of mechatronic systems, offering enhanced adaptability, safety, and versatility. This proposed architecture has provided an overview of the latest innovations in materials, sensing, control, and applications of soft robotics. By further exploring and addressing the challenges, soft robotics can revolutionize various industries, making significant contributions to the advancement of human-robot interaction and automation.

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