

Soft Fluidic Actuators, Fluidic Sensors and Their Integration System

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Abstract: Soft fluidic actuators and sensors play a crucial role in advancing soft robotics. This review presents innovative integration strategies for developing adaptable and efficient robotic systems. The key areas of focus include the design and fabrication of soft hydraulic and pneumatic actuators, the incorporation of advanced sensing mechanisms, and the application of these technologies in various environments such as underwater systems and wearable technologies. The review underscores the interdisciplinary approach driving current research and highlights potential future advancements, particularly in achieving greater autonomy and adaptability in soft robotic systems. This summary aims to provide a foundation for further exploration and innovation in the field, suggesting that ongoing interdisciplinary collaborations and technological improvements will continue to enhance the capabilities and applications of soft fluidic actuators and sensors.

Keywords: Soft Fluidic Actuators; Fluidic Sensors; Integration System.

1. Introduction

Soft robotics, a rapidly evolving domain, focuses on the development of robots that emulate the nature of biological systems[1]. The main emphasis is on soft fluidic actuators and sensors, which are crucial for enhancing the flexibility and functionality of robots. Soft fluidic actuators utilize fluidic systems to achieve movement and adaptability, mimicking the intricate motions found in nature. Similarly, soft sensors enable robots to perceive and interact with their environment in a more detailed manner, thereby broadening the scope of applications in this innovative field. Despite significant advancements, integrating these components into effective systems presents substantial challenges, including design complexity[2], material selection[3], and seamless sensor integration[4]. The design of durable and efficient soft fluidic actuators benefits significantly from expertise in material science to ensure optimal performance. While an understanding of fluid dynamics can inform certain design aspects, it is not the sole requirement for achieving durability and efficiency. Material selection is crucial, as it affects the actuator's performance, longevity, and biocompatibility, particularly in medical applications. Furthermore, the integration of sensors within soft robotic systems must ensure that they can operate without hindering the actuator's flexibility and functionality.

This review paper aims to provide a comprehensive survey of recent developments in soft fluidic actuators and sensors from the past five years (2019-2023). It explores innovative integration strategies that enhance the performance and applicability of these systems across various fields, including medical devices, wearable technology, and autonomous robotics. By analyzing cutting-edge research and synthesizing findings, this paper seeks to highlight the technological synergies and potential pathways for future innovations. The scope of this review is confined to the latest methodologies, materials, and technological advancements relevant to soft fluidic actuators and sensors. The review is structured to first introduce the reader to the foundational concepts and historical developments, followed by a detailed examination of current technologies and their applications, culminating in

a discussion of future directions and challenges. Through this structured approach, the paper aims to provide a clear and thorough understanding of this dynamic field, encouraging further research and development. By illuminating the current landscape and future potential of soft fluidic actuators and sensors, this review seeks to inspire innovation and collaboration among researchers, engineers, and practitioners in the field of soft robotics.

2. Soft Fluidic Actuators

2.1. Soft Hydraulic Actuators

Soft hydraulic actuators have garnered considerable attention within the field of soft robotics owing to their inherent flexibility and adaptability across a spectrum of applications[5][6]. Peters et al. introduced the pioneering concept of hybrid fluidic actuation, amalgamating hydraulic and pneumatic systems to modulate the stiffness properties of soft actuators[7]. Building upon this foundation, Chen et al. further investigated the deployment of water hydraulic soft actuators in underwater robotic systems, delineating three distinct actuator configurations tailored for small-scale autonomous underwater endeavors[8]. In a complementary vein, Wang et al. directed their focused-on refining contact force estimation for hydraulic soft bending actuators used in gripping tasks, proposing a novel methodology devoid of traditional force sensors[9]. Expanding the realm of control mechanisms, Xu et al. introduced a dynamic electrically driven soft valve engineered for the precise control of soft hydraulic actuators, showcasing the capacity for independent control of multiple actuators through a unified pressure source[10]. Beyond robotics, the exploration of hydraulic actuation mechanics extends to botanical domains, Geitmann et al., underscored the significance of circumferential hoop reinforcements in enhancing bending performance within plants[11]. Leveraging soft DEA-based valves, Pocard-Saudart et al. demonstrated precise closed-loop position control of soft hydraulic actuators, illustrating the potential for comprehensive motion control within soft hydraulic robot systems[12]. Addressing the crucial integration of sensors, Sundaram et al. discussed embedded magnetic sensing

mechanisms for feedback control of soft HASEL actuators within multiactuator systems[13]. Meanwhile, Runciman et al. delved into model-based position control techniques for soft hydraulic actuators, achieving commendable positioning accuracy even in the presence of external forces[14]. In the domain of microscale applications, Fuaad et al. introduced an electrostatic-hydraulic coupled soft actuator tailored for micropump applications, offering a novel avenue to enhance micropump performance[15]. Embracing biomimicry, Meng et al. proposed a hydraulic-driven soft robot inspired by earthworm locomotion, specifically aimed at assisting in thrombi dislodgement within artery vessels[16]. Overall, they demonstrated the diverse array of applications and sophisticated control strategies employed in the utilization of soft hydraulic actuators across various robotic systems.

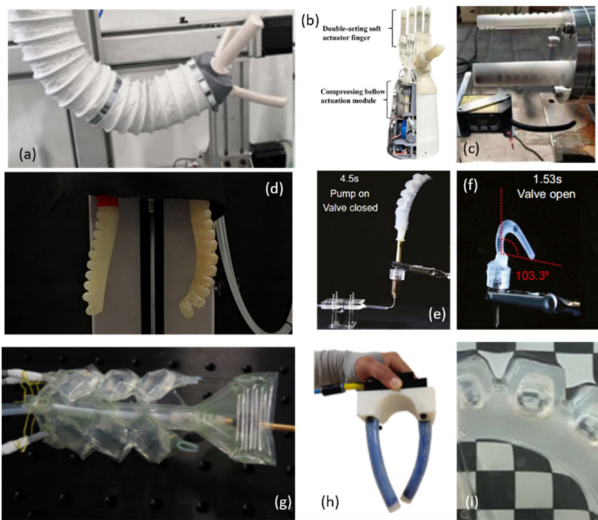


Figure 1. Soft hydraulic actuators. (a) A high-strength soft manipulator integrating soft gripper[17]. (b) Compressing bellow actuation[18]. (c) The water hydraulic flexible actuator[19]. (d) Fully-printable soft actuator[20]. (e) (f) Macro-scale hydraulic soft actuators[10]. (g) Open loop position control of soft hydraulic actuators[21]. (h) Portable soft hydraulic actuators[22]. (i) 3D-printed hydrogel actuator[23]

Figure 1 shows different soft hydraulic actuators. The trend in soft hydraulic actuators encompasses a multidisciplinary approach aimed at enhancing flexibility, adaptability, and control mechanisms for various applications. Researchers are exploring innovative methods such as hybrid fluidic actuation, which combines hydraulic and pneumatic systems for variable stiffness and precise control. Specialized configurations are being developed for specific environments, like underwater robotics, to optimize performance under different conditions. Advanced control mechanisms, including dynamic feedback systems, are being integrated to improve responsiveness and autonomy. Additionally, bio-inspired designs are being employed to mimic natural movements, leading to more efficient and versatile actuators. There is a growing emphasis on interdisciplinary collaboration and the integration of sensor technologies, enabling soft hydraulic actuators to have improved feedback and interaction capabilities across different domains. These trends illustrate a concerted effort to push the boundaries of what soft hydraulic actuators can achieve, paving the way for future innovations in soft robotics.

2.2. Soft Pneumatic Actuators

Soft pneumatic actuators have garnered considerable

attention within the realm of soft robotics due to their capacity to emulate natural movements and provide tactile feedback[24]. Song et al. introduced an innovative soft pneumatic actuator tailored for furnishing tactile feedback within a virtual reality glove system[25]. This actuator becomes operational upon virtual finger contact with an object, thereby delivering tactile sensations to the real fingertip. In a complementary study, Zhou et al. formulated a theoretical framework to assess and predict the deformation of a bending-type soft pneumatic actuator deployed in bionic robotic fish[26]. The empirical findings corroborated the theoretical model's precision in predicting the actuator's responsiveness to actuation pressures. Hohimer et al. investigated the utilization of 3D printed conductive thermoplastic polyurethane/carbon nanotube composites for capacitive and piezoresistive sensing in soft pneumatic actuators, illustrating the feasibility of integrating sensing functionalities into soft robotics through these composite materials[27]. Yang et al. introduced a segmented soft pneumatic actuator inspired by the anatomical structure of earthworms, demonstrating satisfactory agreement between simulated and experimental results concerning bending angle and output force characteristics[28]. Addressing control strategies, Abbasi et al. explored system identification methodologies to delineate the behavior of soft pneumatic actuators for position and force regulation, aiming to design adept controllers to mitigate potential damages in scenarios where conventional rigid robots may incur irreversible harm[29]. Ellis et al. devised a bimodal bending response soft pneumatic actuator utilizing a singular pressure source by integrating a bilinear material, thereby enabling distinct deformation patterns with a mere increase in pneumatic pressure[30]. Hashem et al. introduced a bellows-driven soft pneumatic actuator endowed with self-sensing capabilities to emulate the motions of smooth muscle segments in the stomach, generating linear displacements to mimic smooth muscle contractions[31]. In a related endeavor, Jamil et al. engineered a soft pneumatic gripper employing hybrid optical fibers to gauge bending deformation and contact force at specific finger segments, reinforced with rigid materials to ensure operational resilience in challenging environments[32]. Furthermore, Chauhan et al. tackled the intricacies associated with fabricating complex geometries with desired dimensions and compliance in soft pneumatic actuators for endoscopic applications, unveiling a multi-channel, single-material elastomeric actuator featuring a fully corrugated design inspired by origami principles to cater to specific functionalities in endoscopic procedures[33]. Lastly, Soliman et al. investigated the modeling and realization of a soft biomimetic turtle using echo state network and soft pneumatic actuators, addressing the nonlinear dynamics inherent in soft actuators to accurately simulate the motion of the turtle flipper limb[34]. Collectively, the literature on soft pneumatic actuators underscores a diverse array of applications and design considerations, spanning from tactile feedback systems to bionic robotic fish and endoscopic interventions. Ongoing research endeavors persist in exploring novel designs and materials to augment the capabilities and efficacy of soft pneumatic actuators across diverse domains.

Research on soft pneumatic actuators within soft robotics is marked by a diverse array of innovative applications and design considerations. Trends include the integration of tactile feedback systems, accurate theoretical modeling for deformation prediction, advancements in sensing capabilities

through novel materials, and the exploration of bio-inspired designs. Additionally, there is a focus on robust control strategies, versatile actuator designs, and tailored fabrication techniques to meet the demands of specific applications, indicating a multidisciplinary approach aimed at advancing the capabilities and versatility of soft pneumatic actuators across various domains. **Figure 2** shows different actuator robots designed through biology.

Moreover, soft pneumatic actuators possess significant potential in replicating biological movements, offering unique capabilities in applications such as medical rehabilitation, wearable robotics, and bio-inspired robotic systems. Their lightweight design and fast response times make them suitable for dynamic tasks requiring rapid adjustments and precise control. However, challenges such as achieving high-force output, energy efficiency, and long-term reliability persist. Opportunities for enhancement include the development of new materials that improve durability and performance, the integration of advanced sensing and control technologies for better feedback and adaptability, and the exploration of 3D and 4D printing techniques to create complex actuator geometries. Addressing these limitations through interdisciplinary research can significantly expand the practical applications and effectiveness of soft pneumatic actuators, pushing the boundaries of what these systems can achieve in various fields.

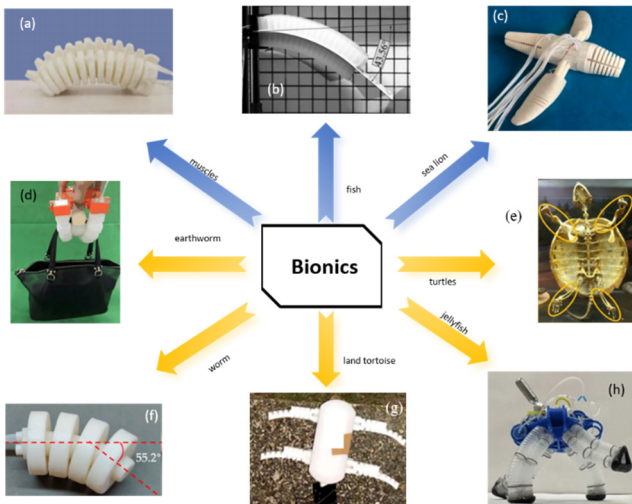


Figure 2. Pneumatic actuator robots designed through bionics. (a) A pneumatic soft-bodied bionic actuator[35]. (b) A bending-type soft pneumatic actuator[26]. (c) A pneumatic amphibious soft bionic robot[36]. (d) Grasping items through actuators[28]. (e) The soft oriented angle pneumatic actuator[34]. (f) A novel crawling soft robot[37]. (g) A 3D-printed tortoise-like soft mobile robot[38]. (h) A jellyfish-like soft robot[39].

2.3. Soft Functional Actuators

In recent years, soft functional actuators have attracted considerable attention owing to their potential utility across diverse domains including soft robotics, flexible electronics, and energy generation. Li et al. demonstrated the efficacy of highly-oriented carbon nanotube thin films as heating electrodes for swift-response soft actuators, thereby highlighting their promise as high-performance flexible electrodes[40]. Moreover, Yu et al. emphasized the importance of multifunctionality in soft actuators and proposed a methodology for achieving multifunctional liquid crystal polymer network soft actuators via direct injection of functional components[41]. Lan et al. concentrated on the design and fabrication of light-driven liquid crystalline

networks and soft actuators featuring controlled molecular motors, thereby underscoring their potential in fostering the development of untethered intelligent soft robots and advanced functional devices[42]. Tawk et al. provided an extensive review of 3D-printable soft pneumatic actuators and sensors, delving into the challenges and opportunities associated with the development of robust and functional soft actuators for soft robots[43]. Furthermore, Kladovasilakis et al. stressed the importance of designing intelligent and multifunctional tools using additive manufacturing and smart control systems, unveiling a novel multifunctional bioinspired soft actuator equipped with a pneumatic motion system[44]. Zhang et al. proposed a modular soft gripper incorporating combined pneumatic actuators, underscoring the versatility and substantial bending deformation capabilities of soft pneumatic-network actuators[45]. In summary, the literature review on soft functional actuators highlights advancements in materials, design strategies, and fabrication techniques aimed at enhancing the functionality and versatility of soft actuators for various applications in soft robotics, flexible electronics, and energy generation. The integration of multifunctionality, self-sensing capabilities, and additive manufacturing technologies emerges as pivotal areas of focus in the development of intelligent and bionic soft actuators.

The studies collectively emphasize a trend towards advancing the functionality and versatility of soft actuators through innovative materials, multifunctionality, biomimetic design, additive manufacturing, and the integration of sensing capabilities. Future research is likely to focus on further material innovation, including the exploration of novel carbon-based materials, as well as the integration of multifunctionality into soft actuators for enhanced performance and adaptability. Additionally, there is a growing emphasis on biomimetic design principles and additive manufacturing techniques to enable rapid prototyping and customization of soft actuator systems.

3. Soft Fluidic Sensors

3.1. Soft Integrated Sensors in Fluid Dynamics

The integration of soft actuators and sensors within fluid dynamics has led to significant advancements in scientific and engineering disciplines. Soft actuators, known for their flexibility, adaptability, and ability to undergo large deformations, have revolutionized traditional approaches to fluid control and interaction, while, soft sensors have enhanced the precision and responsiveness of fluid dynamics systems by providing real-time data and feedback. This synergy between soft actuators and sensors has led to innovative applications ranging from underwater robotics to biomedical devices. Chen et al. introduced a pioneering control system for fiber-reinforced soft bending actuators, using on/off valves for precise manipulation[46]. Wang et al. discussed parameter identification and model-based nonlinear robust control strategies for fluidic soft bending actuators, incorporating second-order dynamics into their control approach[47]. Chen and Zou proposed an adaptive robust control approach using an empirical nonlinear model to enhance control performance[48]. Wang et al. presented a computationally efficient dynamical model for fluidic soft actuators, validated experimentally[49]. Xavier et al. explored nonlinear estimation and control of bending soft pneumatic actuators using feedback linearization and the

Unscented Kalman Filter (UKF)[50]. Ibrahim et al. investigated both linear and nonlinear low-level control strategies[51]. Cao et al. developed a model-based robust tracking control method for soft bending actuators without observers[52], while another study by Cao et al. proposed an observer-based continuous adaptive sliding mode control strategy to improve robustness and adaptability[53]. This review underscores the imperative for robust and functional soft actuators and sensors in addressing the complex challenges posed by fluid dynamics environments. The intricate motions and high nonlinearity of soft materials pose obstacles for force output, modeling, and sensory feedback. Recent work of soft actuators and sensors in fluid dynamics is shown in Table 2. To address these limitations, a novel Soft Origami Optical-Sensing Actuator (SOSA) with integrated actuation and sensing capabilities exemplifies the need for innovative solutions in underwater applications. The field is poised to embrace interdisciplinary collaboration to enhance soft actuators and sensors for fluid dynamics applications. By leveraging advancements in materials science, manufacturing techniques like 3D printing, sensor integration, and control systems, researchers aim to develop multifunctional, adaptive, and intelligent systems capable of precise fluid environment navigation and manipulation. The ongoing pursuit of innovation in this field promises to redefine the boundaries of what can be achieved with soft actuators and sensors, leading to more advanced and versatile applications in soft robotics, environmental monitoring, and medical devices.

Furthermore, there's a notable shift towards innovative approaches like reservoir computing and Soft Origami Optical-Sensing Actuators, indicating a future direction towards more autonomous and multifunctional soft robotic systems.

3.2. Current Progress in Soft Sensor Technologies

Soft robotics has emerged as a rapidly advancing domain, witnessing notable progress in recent years, especially from 2019 to 2024. Walker et al. conducted a thorough review elucidating recent advancements in soft pneumatic actuators, focusing on control systems, materials, construction, modeling, and sensor integration[54]. Yap et al. investigated the utilization of 3D printing techniques and materials in soft robotics, emphasizing the advantages of polymer 3D printing methodologies[55]. Saleh et al. introduced a novel geometrical parameter for soft pneumatic actuators, showcasing the potential for adaptable work envelopes and tip forces in applications[56]. Together, these studies collectively underscore the diverse array of advancements and innovations within the realm of soft robotics, laying the groundwork for promising future developments in the field.

Expanding on these advancements, recent research has explored novel avenues to enhance the capabilities of soft robotics in fluidic environments. For instance, advancements in soft pneumatic actuators have led to the development of mechanisms capable of mimicking fluid dynamics with unprecedented precision. By incorporating principles inspired by fluid dynamics, such as laminar flow and turbulence, soft actuators can achieve more natural and efficient movements, enabling applications in areas such as aquatic exploration and environmental monitoring. Furthermore, the integration of soft robotic fish swarms with advanced sensor technologies offers new possibilities for underwater exploration and surveillance. These bio-inspired systems not only navigate

fluidic environments seamlessly but also gather real-time data on water quality, temperature gradients, and marine life behavior, contributing to ecological research and environmental conservation efforts. Moreover, the soft robotic systems with stretchable capacitive sensors opens avenues for enhanced tactile perception and interaction with fluidic environments. These sensors enable soft robots to detect subtle changes in pressure and texture, facilitating tasks such as object manipulation and grasping in dynamic fluidic environments. Overall, the integration of soft robotics with advancements in fluid dynamics holds promise for revolutionizing various industries, from marine exploration to industrial automation. As interdisciplinary collaboration continues to drive innovation in both fields, we can expect further breakthroughs that will expand the capabilities and applications of soft robotics in fluidic environments. The studies in soft robotics indicate advancements in materials science, manufacturing techniques like 3D printing, sensor integration, and control systems. Notably, there's a focus on democratizing access to research through open-source designs, fostering collaboration and accelerating development. Moreover, the studies underscore a growing emphasis on enhancing the versatility, adaptability, and functionality of soft robotic systems through innovative approaches, which are likely to continue shaping the field's trajectory in the future. **Figure** shows the recent soft fluidic robotics.

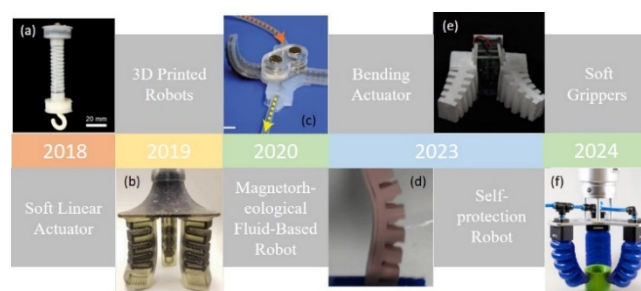


Figure 3. Recent soft fluidic robotics. (a) Reverse pneumatic artificial muscles[57]. (b) Immediately deployable for real-world applications[58]. (c) Magnetorheological fluid-based soft robots[59]. (d) Modeling of soft fluidic actuators[60]. (e) Self-protection soft fluidic robots[61]. (f) A soft gripper with four pneumatic actuators[62].

4. Conclusion

This paper has reviewed recent advancements in soft fluidic actuators and sensors, emphasizing their integration within various systems. The developments in material science, fabrication techniques, and control strategies have enabled significant progress in soft robotics, enhancing their adaptability, precision, and functionality. These technologies show immense potential for diverse applications, from biomedical devices to environmental monitoring. Future research should focus on further improving the performance, reliability, and integration of these systems to fully harness their capabilities.

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