A systematic review of mobile soft robots

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Abstract: This article presents a comprehensive review of the advancements in mobile soft robotics, highlighting their design, actuation mechanisms, and performance capabilities. The objective is to examine the fastest and most capable mobile soft robots, emphasizing their diverse approaches and technologies for various environments. A systematic literature review was conducted using IEEE Xplore and Scopus databases, focusing on mechanical models, actuation methods, and performance metrics. Results show that the Tunable Dynamic Walking robot, using vibration through soft twisted beams, achieved the highest speed of 156.30 mm/s. Additionally, the Untethered Crawling Robot, employing pneumatic actuation, demonstrated the highest payload capacity of 6000 g. These findings underscore the significant progress in speed, mobility, and payload capacities of mobile soft robots. The study emphasizes the importance of continued research in enhancing the functionality and adaptability of these robots for real-world applications, including inspection, surveillance, and environmental monitoring.
Keywords: Mobile soft robots; actuation mechanisms; robotics; inspection; surveillance; pneumatic.

1. Introduction

The field of robotics has evolved significantly, introducing innovative concepts such as soft robots, which differ from traditional robots in their flexibility and adaptability [1]. Soft robots are constructed with pliable materials that allow for more natural and safe movements, especially in interactions with humans and delicate structures [1]. This approach contrasts with traditional rigid robots, which, while robust, may be limited in applications requiring subtlety and compliance [2].

Within the vast universe of soft robots, there are various categories, including inflatable robots, robots based on electroactive polymers, and robots that use fluid-based actuation mechanisms. Each of these types has unique characteristics that make them suitable for different applications [3]. For instance, inflatable robots can be used in environments where safety is paramount, while robots using electroactive polymers can be more efficient in tasks requiring precision and detailed control [4][5].

A distinction within the field of soft robotics is between static soft robots and mobile soft robots. Static soft robots are typically anchored to a fixed position and are designed for tasks such as manipulation, gripping, and interaction with their immediate surroundings. They excel in applications where their soft, adaptive nature can be used to handle delicate objects or perform complex, nuanced movements without the need for relocation [6].

In contrast, mobile soft robots combine the flexibility of soft robots with the ability to move through their environment. This mobility allows them to navigate complex and dynamic spaces, making them ideal for applications such as inspection, surveillance, and environmental monitoring [7]. Pneumatic systems use compressed air to create movement, mimicking the motion of muscles for smooth and adaptive actions [8]. Dielectric elastomers are electrically active polymers that change shape when an electric field is applied, providing lightweight and precise movements. Fluid-based actuation involves using hydraulics or liquid metals to produce strong and stable movements [9]. Additionally, vibration-based mechanisms use controlled vibrations to navigate uneven or complex terrains with precision [5].

This article aims to provide a comprehensive overview of the current state of mobile soft robots, focusing on their design, actuation mechanisms, and performance capabilities. By examining the fastest and most capable mobile soft robots, we highlight the diverse approaches and technologies developed to enhance robot performance in different environments.

Furthermore, we explore the payload capacities of these robots, emphasizing the practical implications of their ability to carry and manipulate various loads. The diversity in actuation methods and payload capabilities demonstrates the potential of soft robots to address a wide range of tasks, from heavy lifting to delicate handling. The findings presented in this article underscore the importance of continued research and development in the field of mobile soft robotics, aiming to further improve the functionality and adaptability of these innovative machines.

2. Methodology

This study conducted a comprehensive literature review focusing on mobile soft robots, utilizing two primary academic databases: IEEE Xplore and Scopus. The objective was to identify and analyze mechanical models of mobile soft robots that have been successfully implemented or have the potential to inspire new prototypes.

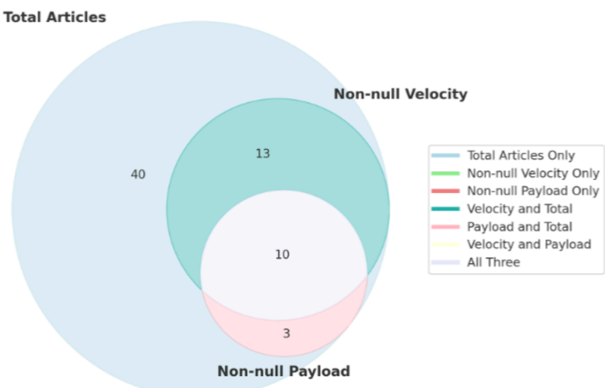
The following steps were undertaken in the methodology:

- Database Selection and Search Strategy: A systematic search was performed on IEEE Xplore and Scopus using specific keywords related to mobile soft robotics, such as "mobile soft robot," "soft robotics," "actuation mechanisms," and "locomotion." The search was restricted to articles published within the last ten years to ensure the inclusion of the most recent advancements in the field.
- Inclusion and Exclusion Criteria: The inclusion criteria focused on articles that described mechanical models of mobile soft robots, their actuation methods, and their performance capabilities. Articles were excluded if they did not provide sufficient experimental data or detailed descriptions of the robots' design and functionality. This analysis can be shown in Figure 1.
- Data Extraction: Relevant information was extracted from the selected articles, including details on actuation methods, speeds, payload capacities, environments in which the robots operate, and their

capabilities for forward movement, turning, and vertical motion. This data was systematically organized into tables to facilitate comparison and analysis.

- Quantitative and Qualitative Analysis: A bibliometric analysis was conducted using the Bibliometrix [10] tool to perform both quantitative and qualitative evaluations of the collected data. The quantitative analysis included metrics such as citation counts, publication trends, and the geographical distribution of research. The qualitative analysis focused on identifying common themes, challenges, and innovative solutions in the design and actuation of mobile soft robots.
- Comparison and Evaluation: The extracted data was compared to identify the fastest and strongest actuation methods and design approaches. This comparative analysis provided insights into the strengths and limitations of current mobile soft robotic technologies.
- Critical Review and Future Directions: Based on the analysis, a critical review was conducted to summarize the key findings and highlight the potential areas for future research. Recommendations were made for improving the design, functionality, and adaptability of mobile soft robots, with a focus on enhancing their practical applications in real-world scenarios.

Figure 1: Venn diagram of searched articles



By following this structured methodology, the study aimed to provide a thorough understanding of the current landscape of mobile soft robotics and to identify promising avenues for further innovation and development.

3. Results and Discussion

Mobile soft robots have shown advancements in speed and mobility, achieved through various actuation methods. However, the maximum speed of a robot can limit its application in different environments, as low-speed robots are not suitable for long-distance navigation. Table 1 provides a comparison of some of the fastest soft robots, highlighting their actuation mechanisms, speeds, and capabilities in different environments.

The Table 1 presents the five fastest soft robots from the articles database, detailing their tethered status, actuation methods, maximum speeds, environments, and capabilities for forward movement, turning, and vertical motion. Tethered robots are connected to external power sources via cables, while untethered robots operate independently with onboard power. Each robot is referenced by its corresponding research article.

The Tunable Dynamic Walking robot (Table 1, item 1) is tethered and utilizes vibration through soft twisted beams for actuation, reaching the highest speed of 156.30 mm/s among the compared robots. Designed for ground environments, it excels in both forward movement and turning, although it lacks vertical motion capability. This robot is referenced by the study [11].

The Insect-Scale Robot (Table 1, item 2) employs dielectric elastomer actuators and is untethered, achieving a significant speed of 100.00 mm/s. It is also designed for ground environments, capable of forward movement and turning, but does not support vertical motion. This robot is documented in the study [12].

A versatile example, the Soft Wall-Climbing Robot (1, item 3), uses dielectric-elastomer artificial muscles for actuation and is untethered. It can achieve speeds of 88.46 mm/s and is capable of forward movement, turning, and vertical motion. This robot's ability to climb walls, in addition to moving on the ground, makes it suitable for various inspection and surveillance applications. This robot is referenced in the study [13].

The DECSO robot (Table 1, item 4) is another untethered robot that uses pneumatic actuation to reach speeds of 75.00 mm/s. It excels in forward movement and turning in ground environments, although it does not support vertical motion. This robot is documented in the study [14].

The Thick Miniatured Mobile Soft Robot (Table 1, item 5) employs pneumatic actuators and, while its speed is lower at 31.50 mm/s, it supports forward movement, turning, and vertical motion. This capability highlights its potential for navigating complex terrains and environments. This robot is referenced in the study [15].

The diversity in actuation methods and capabilities among the fastest mobile soft robots is evident. Each robot brings unique advantages tailored to specific environments and tasks, from ground-based operations to vertical climbing and complex terrain navigation. In terms of speed, the vibration through soft twisted beam type actuation achieved the best results with 156.30 mm/s, and this is probably due to the high operating frequency that this actuator requires.

The payload capacity of mobile soft robots is a critical parameter that defines their practical applications and functional capabilities. This capacity affects their ability to couple with sensors, transport equipment, and determines the amount of batteries the robot can carry. Table 2 provides a comparative analysis of several soft robots based on their tethered status, actuation methods, payload capacities, environments, and movement capabilities, including forward movement and turning.

Table 1: Fastest mobile soft robots by speed

Item	Name	Thethered	Actuation	Speed (mm/s)	Environment	Forward moviment	Turn	Vertical motion	Reference
1	Tunable Dynamic Walking	X	vibration through soft twisted beams	156.30	Ground	V	V	X	[11]
2	Insect-Scale Robot	V	dielectric elastomer	100.00	Ground	V	V	X	[12]
3	soft wall-climbing robot	V	dielectric-elastomer artificial muscles	88.46	Ground	V	V	V	[13]
4	DECSO	V	pneumatic	75.00	Ground	V	V	X	[14]
5	Thick Miniatured Mobile Soft Robot	V	pneumatic	31.50	Ground	V	V	V	[15]

The Untethered Crawling Robot (Table 2, item 1) is tethered and utilizes pneumatic actuation, boasting the highest payload capacity of 6000g among the listed robots. It is designed for ground environments and supports both forward movement and turning. This robot's significant payload capacity underscores its potential for applications requiring heavy lifting and transportation. The reference for this robot is provided by [16]. The pneumatic actuators proved to be more capable of carrying more load than the vibration-actuated ones, suggesting that the load distribution generated by the pneumatic system is more effective, as proven experimentally.

The Laser Pouch Motors robot (Table 2, item 2) also operates tethered and employs a liquid-to-gas phase change mechanism for actuation, with a payload capacity of 750g. Designed for ground environments, it is capable of forward movement but lacks data on its turning capabilities. This innovative actuation method allows the robot to manage substantial loads efficiently. The robot is referenced by [17].

The Legged Robot (Table 2, item 3) is untethered and uses pneumatic actuation to carry a payload of 620g. It is designed for ground environments and supports both forward movement and turning. This robot's design and functionality highlight its adaptability and robustness in navigating various terrains while carrying moderate loads. The reference for this robot is provided by [18].

The Tripod Mobile Robot appears twice in the table with two different actuation mechanisms. The first instance (Table 2, item 4) uses soft membrane vibration for actuation, enabling it to carry a payload of 500g. It is untethered, designed for ground environments, and supports both forward movement and turning. This robot's soft membrane vibration mechanism offers a unique approach to payload management, making it suitable for delicate handling tasks. The reference for this robot is [19].

In its second instance (Table 2, item 5), the Tripod Mobile Robot employs a vibration mechanism for actuation, with a lower payload capacity of 100g. Like its counterpart, it is untethered and supports both forward movement and turning, designed for ground environments. This configuration highlights the trade-offs between different actuation methods and payload capacities, showcasing the flexibility of design in soft robotics. The reference for this version of the robot is provided by [20].

Table 2: Mobile soft robots ordered by payload capacity

Item	Name	Thethered	Actuation	Payload	Environment	Forward moviment	Turn	Reference
1	Untethered Crawling Robot	X	Pneumatic	6000 g	Ground	V	V	[16]
2	Laser Pouch Motors	X	Liquid-to-Gas Phase Change	750 g	Ground	V	NaN	[17]
3	legged robot	V	Pneumatic	620 g	Ground	V	V	[18]
4	Tripod Mobile Robot	V	Soft Membrane Vibration	500 g	Ground	V	V	[19]
5	Tripod Mobile Robot	V	Vibration Mechanism	100 g	Ground	V	V	[20]

In summary, the payload capacities of these mobile soft robots demonstrate a wide range of capabilities, from carrying heavy loads to managing delicate payloads. The diversity in actuation methods, such as pneumatic actuation, liquid-to-gas phase change, and vibration mechanisms, illustrates the innovative approaches in the field. The pneumatic robot "Untethered Crawling Robot" was able to support more weight, and this is because of this and its actuation system that guarantees better support than "Tripod Mobile Robot".

4. Conclusion

This study has provided a comprehensive review of the advancements and current state of mobile soft robotics. By analyzing various mechanical models and their actuation mechanisms, we have highlighted the significant progress made in the field, particularly in terms of mobility, adaptability, and payload capacities. The diversity in actuation methods, such as pneumatic systems, dielectric elastomers, and vibration-based mechanisms, underscores the innovative approaches that have been employed to enhance the performance of mobile soft robots.

The comparative analysis of the fastest and most capable mobile soft robots revealed that each robot brings unique advantages tailored to specific environments and tasks. From ground-based operations to vertical climbing and complex terrain navigation, these robots demonstrate the potential for widespread applications, including inspection, surveillance, and environmental monitoring. This review found that robot Tunable Dynamic Walking with actuation model vibration through soft twisted beams had the fastest performance.

Moreover, the payload capacities of these robots show a wide range of capabilities, from heavy lifting to delicate handling, further emphasizing their versatility. Here it was found that the pneumatic actuation model had the best performance supporting 6000g load. The findings indicate that continued research and development in mobile soft robotics are essential to address the existing challenges and to optimize the design and functionality of these robots.

Future research should focus on exploring new actuation mechanisms, improving multifunctional capabilities, and enhancing the adaptability of mobile soft robots to various real-world scenarios. By building on the current advancements, the field of mobile soft robots can continue to evolve, offering innovative solutions for a broad spectrum of applications.

In conclusion, the ongoing development and refinement of mobile soft robots hold great promise for the future, with the potential to revolutionize the way we approach tasks in challenging environments. The insights gained from this study provide a solid foundation for future innovations and practical implementations in the field of soft robotics.

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