Biology-Inspired Innovations in Soft Robotics for Efficient Locomotion

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Inspired by nature, soft robotics promises to overcome traditional robots' limitations by using the flexibility and adaptability of living organisms to navigate complex environments. This field aims to replicate natural movements, such as the peristaltic motion of earthworms, applying them to robots to enhance locomotion and manipulation capabilities. Research focuses on developing prototypes inspired by biological mechanisms, with significant advances in design, actuation, and control, highlighting applications in challenging environments. Studies include the development of mobile robots with pneumatic actuation and models that mimic earthworm locomotion and exploring the use of friction for efficient movement. Soft robotics points to a future with more adaptable and efficient robots, promising innovations in inspection, exploration, and medicine, thanks to integrating new materials, actuators, and control algorithms.
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Inspired by the principles and mechanisms found in nature, soft robotics emerges as a promising field to overcome the limitations of traditional, rigid robotic systems [1,2]. This biomimetic approach seeks to replicate living organisms' adaptability, flexibility, and resilience, allowing the development of robots capable of performing complex tasks in varied and challenging environments [3].

By imitating biological structures, such as the peristaltic movements of earthworms and the deformation capacity of certain invertebrates, soft robotics offers innovative solutions for problems of locomotion, manipulation, and interaction with the physical world.

This expanded summary explores recent advances in this field, highlighting the main innovations in the design, performance, and control of soft robots and discussing their potential applications and impact on future robotic technology [4].

Materials and Methods

A search for articles focused on mobile soft robots was conducted using the IEEE Xplore and Scopus databases. The search targeted mechanical models of mobile soft robots that could be reproduced or inspire other prototypes.

Of the twenty-five articles found, nine addressed the development of robots that fit the specified descriptions, focusing on the mechanical development of mobile robots, whether actuated via cables or pneumatics. These models will be briefly described throughout the article.

Results and Discussion

Research in soft robotics has advanced significantly, drawing inspiration from biology to develop robotic systems capable of efficient and adaptable locomotion in different environments. This section highlights recent innovations in soft robotics, focusing on locomotion mechanisms inspired by organisms such as earthworms and other invertebrates, which demonstrate peristaltic movements and deformation capabilities.

Earthworm-Inspired Locomotion

The locomotion of the earthworm (Figure 1) demonstrates peristaltic movement through a harmonic sequence of muscle contractions and relaxations in its segmented body. The contraction of the circular muscles, followed by the relaxation

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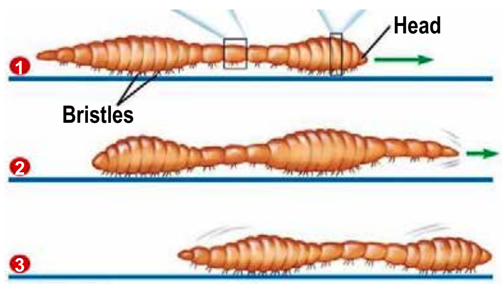
Figure 1. Mechanism of locomotion of an earthworm.



of the longitudinal muscles in alternating segments, drives the worm forward, creating an effective wave-like movement. This mechanism has been used as inspiration for soft robots with diverse applications.

Meshworm: A Soft Peristaltic Robot

The Meshworm robot [6] uses peristaltic locomotion, inspired by the movement of earthworms, through the sequential contraction and relaxation of antagonistic actuators made of nickel-titanium (NiTi) coils. A proprioceptive design with potentiometers allows closed-loop control, offering precise feedback about the robot's position. This approach enables Meshworm to navigate challenging environments while maintaining flexibility and resistance to significant external impacts.

Pneumatic Actuation Systems

A soft pneumatic robot designed for efficient locomotion in tubes features a structure composed of extendable pneumatic actuators and flexible feet [7]. This design optimizes the locomotion cycle, reducing the steps required to move. The phenomenological modeling of the robot, based on mathematical expressions, facilitates simulation and manufacturing, providing an accurate representation of its behavior.

Integrated Rotary Propeller Drive Mechanism with Capability for Smooth Peristaltic Movement

The article focuses on the design method of a Wave Wheel robot [8], which can generate continuous and smooth peristalsis driven by a clustered rotating propeller drive mechanism. When a single motor turns the propellers, the wheel generates peristaltic waves. The proposed mechanism has unique features: It can generate smooth peristalsis with a simple structure, be driven by a single motor, and propagate waves at high speed due to the infinite rotation of the shaft. Its structure is circular in the transverse plane and can be used as an omnidirectional drive wheel. The prototype, with a diameter of 57 mm, reached a maximum peristaltic locomotion speed of 43 mm/s when the angular speed of the propeller was 60 rad/s.

Friction-Based Locomotion

The significance of friction in facilitating the locomotion of soft robots has been underscored by the advancement of control systems that leverage friction to enable crawling movements [9]. Numerical simulations and real-time controllers based on friction feedback have been developed and implemented, showcasing the viability of this approach for achieving efficient locomotion.

Innovations in Actuation and Control

Various approaches have been investigated to improve soft robots' peristaltic locomotion [10] since specialized actuators produce peristaltic waves to lift structures inspired by scissor mechanisms and utilize electroactive polymeric materials [5]. These innovations aim to streamline mechanical design, minimize energy usage, and ensure effective motion efficiency in soft robots.

Conclusion

Advancements in soft robotics, drawing inspiration from biology, showcase considerable potential for developing robots capable of navigating and operating in challenging environments. The mimicry of biological mechanisms offers insights into designing more adaptable and resilient robots and paves the way for innovative applications in inspection, exploration, and medicine. The integration of advanced materials, efficient actuators, and intelligent control algorithms remains a promising frontier in the field of soft robotics.

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