From Earthworms to Robotics: A Review of Worm-Like Locomotion Systems

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Abstract. Worm-like bionic robots that are inspired by soft-bodied invertebrate locomotion, such as nematodes and earthworms, are one emerging trend in soft robotics. With inherent abilities to adapt and change shape to narrow or uneven environments, such robots have special application prospects for pipeline inspection, search and rescue, and minimally invasive medicine. The current review provides a synthetic account of recent advances within structural designs, actuating technologies, and control policies for these robots. The paper explores biologically grounded modes of motion such as peristalsis, undulation, and inchworm motion, and how morphological designs and material selections impact locomotion performance. Beneath this, this paper mentions challenges with actuation autonomy, soft sensing, and gait management, while highlighting future trends such as multimodal locomotion, intelligent management, and tunable material systems. By correlating biological inspiration with engineering expertise, this paper provides a road map to further refinement and real-world application of worm-like robotic systems.While this review offers a comprehensive synthesis of worm-like bionic robots, it is limited by the lack of standardized benchmarking across existing studies, which hinders objective performance comparison; future research should address this gap and explore bio-hybrid approaches to further improve locomotion efficiency, adaptability, and autonomy.

Keywords: Worm-like bionic robots, soft robotics, biologically inspired locomotion, actuation technologies.

1. Introduction

In recent years, bioinspired robotics has emerged as a multidisciplinary field. Worm-like soft-bodied locomotion offers efficient, adaptable movement in complex environments, inspiring robots capable of navigating terrains where rigid systems fail [1]. Natural worms, such as earthworms (Lumbricus terrestris), nematodes (Caenorhabditis elegans), and inchworms (Geometridae larvae), demonstrate extraordinary mobility in unstructured, constrained, and heterogeneous environments. Such robots make use of deformation of the body and rhythmic entrainment rather than stiff joints to progress along rugged terrain [2]. The ability to move along narrow tubes, dig along soil, swim along fluids, or walk along uneven grounds offers a most interesting basis upon which to construct robots that can operate under conditions that stiff robots are not capable of managing [3].

Worm-like bionic robots are designed to summarize these natural capabilities by mirroring structural as well as functional characteristics of annelid as well as nematode movement. The robots are usually composed of compliant or module components that can contribute to elongation, contraction, as well as wave-like body motions. Compared to stiff moveable platforms, worm-like soft robots have distinctive advantages within suppleness, safety, as well as robustness. They can adapt to change their form to suit within an ambient, reduce harm to soft constructions, as well as absorb mechanical shocks that will disable conventional devices [4]. Thus, they were increasingly helpful within missions that need to move within narrow locations—such as pipeline inspection, endoscopic surgery, search-and-rescue missions, as well as underwater robots. The evolution of worm-like robotic systems has been quickly growing within the previous decade with contributions from advances within actuation technologies, material science, as well as algorithmic controls [5]. Pneumatic, hydraulic, as well as electroactive actuation systems made new modes of movement feasible that mimic biological peristalsis as well as undulation. Despite these advancements, numerous challenges remain. The trade-offs between power density and response speed, the integration of sensing and autonomy, and the scaling of designs for either micro-medical or large-scale industrial uses remain open problems. Additionally, achieving robust multimodal locomotion—combining peristaltic crawling, undulatory swimming, and anchoring mechanisms in a single platform—requires further breakthroughs in mechanical and computational design [6][7]. This review aims to provide a comprehensive and up-to-date synthesis of the field of worm-like bionic robotics. This paper categorize current technologies according to their biological inspiration, actuation mechanisms, structural design, control strategies, and sensing capabilities. This study also highlight emerging application areas and evaluate existing challenges, before outlining key directions for future research .

2. Biological Inspiration and Taxonomy

2.1 Earthworm-Inspired Peristalsis

Earthworms use a form of locomotion known as peristalsis, characterized by coordinated, sequential contractions of longitudinal and circular muscles. This results in elongatory and segmental compression so that while one portion of the body is thrust forward, rest of the body can be anchored by radial expansion. The process is further supplemented by chaetae (bristle like protrusions) that provide directional friction with the matrix that surrounds [8]. Robots designed with an earthworm strategy emulate this technique by subdividing own bodies into modules that contract and expand by periodic motion. The mode is best adapted to pipeline or underground application, such that with suitably matched propulsion and anchoring force, optimum thrust results.

2.2 Nematode-Inspired Undulation

Nematodes, such as Caenorhabditis elegans, move by lateral undulations of the body that produce propulsive waves along head-to-tail axes. Such movement significantly relies upon differential friction between ventral and dorsal body surfaces as well as upon environmental media's viscoelastic properties. Under conditions of low-resistance media such as fluids or lubricated surfaces, undulatory movement can form continuous propulsion without discrete points of anchoring. Robotic nematode counterparts typically include continuous- or cable-driven flexible bodies that are able to form sinusoid waves. They are suitable for underwater operations as well as soft-surface operations and may be capable of high maneuverability with rather limited input of energy [9].

2.3 Inchworm-Inspired Extension and Anchoring

Inchworms exhibit distinctive locomotion patterns that include intermittently securing the front and rear ends of the body and extending the central part. The result is a “looping” gait that is mechanically simple but effective at climbing up walls or squeezing along narrow corridors. Robots that embrace inchworm style locomotion usually feature mechanical gripping mechanisms or vacuum suction cups with telescoping actuation systems. Such designs are particularly ideal at climbing up sheer surfaces, exploring pipes, or working on rugged surfaces where firm gripping is at a premium. They are very scalable and can cope with multi-modal data very well.

3. Actuation Technologies

These actuation systems are the mechanical proof for bending, teams moving and avoiding obstacles of such bionic robots. As these robots are soft or have segmented bodies to mimic biological motion, the traditional rigid actuation system is not suitable. Rather, the field has progressed to more specialized driving technologies, focusing on compliance, compactness and decentralised motion control. The methodology for actuation mechanism affects the performance of the robot with respect to speed, output force, energy efficiency and environmental adaptation. One of the major actuation methods in worm-like robots is pneumatic or hydraulic actuation. Such systems inflate and deflate internal chambers with compressed gas or liquid to achieve linear or radial deformations. Pneumatic actuators, such as McKibben muscles and soft bellows, can achieve high displacement and force outputs with low mass. They work especially well in capturing the peristaltic action of an earthworm, where local elongation can pin a segment while its neighbors contract. But the reliance of fluid actuation on external pumping and tubing presents a major drawback in limiting autonomy and adding substantial design complication. In addition, response times may be limited by the viscosity of the working fluid and the properties of the control system [10].

In particular Shape Memory Alloys (SMAs) represent a competitive actuation technique, in particular when miniaturization is of concern. SMAs compress on heating and return to their original length on cooling, showing that no moving parts are needed to realize straight actuators. Such materials are appealing for having both high energy density and low mechanical complexity. However, their small temperature response time and poor cycling stability are not desirable for the continuous or high-frequency movement. Moreover, the often high power demands of the phase transition heating might not be suitable to minature or battery power convolution, particularly for untethered medical uses. There is also a group of actuators that may have potential for worm-like propulsion, which are termed Electroactive Polymers (EAPs). Under the influence of an electric field, EAPs deform, and bending, twisting, or expansion are possible. Owing to their silent actuation, good compliance, and structural simplicity, they can be a promising candidate for soft robotic systems. However, force output of EAPs is generally low, and they usually need high driving voltage, so it restricts their present use in compact and lightweight devices. Active research in the development of techniques to increase their robustness and scalability is ongoing [11].

4. Structural Design and Materials

4.1 Structural Design

The compliant, segmented, and geometrically adaptable nature of worm-like bionic robots fundamentally drives their morphology. Taking inspiration from nature creatures earthworm and nematode, frog or snake-like soft robotic designs follow two types of structural paradigms: (i) modular segmentation and (ii) continuous soft bodies. Modular segmented robots consist of an array of discrete modules that are regularly repeated and can move independently from each other. It is inspired by the metameric structure of annelids and allows the local actuation of segments that can replicate the peristaltic or inch worm motion. A typical module will have an actuator, sensor and in some cases embedded control electronics. This modular design enables easy hardware scaling, fault tolerance, and maintainability. For example, any individual damaged link can be replaced, without such replacement affecting the rest of the robot. Segment-based coordination also enables robots to rapidly recover and adjust gaits in the presence of parameter variations on rough terrains [12].

4.2 Control Systems

Affordable, worm-like robots that crawl really well need more than just mechanical flexibility; they also need sophisticated control systems that are capable of accounting for changes to the environment and the body and keeping the robot’s gait stable. Control in such robots extends from basic open-loop feed-forward to complex bio-inspired neuro-architecture. A common paradigm is the application of predefined gait patterns, especially when the robot has limited sensory feedback or operates in constrained environments. These gaits are timing and amplitude patterns of segmental actuation, which are defined along a cycle and are usually computed off-line. This approach is useful when applied to well-defined environments but performs poorly when exposed to unstructured and/or dynamic environments. To overcome this constraint, several of works have focused on CPGs -- neural-based networks that generate rhythmic signals. CPG-based controllers produce smooth, coordinated waveforms that in some ways mimic those of natural organisms. They are also capable of modulating frequency and phase relationships in real-time due to changes in ground type or sensory feedback which facilitates online gait switching. Make feedback control its center, ameliorate the robustness of the system. Proprioceptive sensors, as stretch sensors, soft strain gauges, or embedded IMUs, give informations on the robot internal deformation and posture [13].

Exteroceptive inputs, e.g., contact sensors or pressure arrays, feed the robot with information about its interaction with the environment. These feedback loops enable the robot to adapt segment timing, contact force, or motion amplitude during operation, leading to greater stability and efficiency. Machine learning methods are used more recently, especially reinforcement learning (RL), to adapt control policies in unknown or complex terrains. Such data-driven methods provide robots the ability to learn efficient gaits implicitly, without direct programming, and thus can account for morphological adaptations like load changes or slight damage. Hybrid control architectures are also becoming popular that combine model-based planning with learning-based adaptation. This combination enables structured motion planning, while remaining responsive to unmodeled disturbances. For multi-modal soft robotic locomotion, which can perform peristalsis, undulation, anchoring, etc., high-level controllers decide which mode of locomotion to employ, given sensory feedback and a particular task to be achieved [14].

The coordinated control method is a key content determining the overall function of the worm-like bionic robot combined with the structure design. The next generation of advancements are expected on the basis of co-design framework which couples material behavior and mechanics, alongside close-loop control on orders to develop systems that are increasingly autonomous, robust and environmental adaptive.

5. Application Domains

Worm-like bionic robots have demonstrated significant potential across a range of application domains, particularly those involving confined, cluttered, or sensitive environments where traditional rigid robots struggle to operate. One of the most prominent areas is industrial inspection, especially in the context of pipeline monitoring and maintenance. The elongated, flexible structure of these robots allows them to navigate through narrow, curved, or branching ducts without damaging the surrounding infrastructure. Equipped with onboard cameras, leak detectors, or structural sensors, worm-like robots can perform autonomous inspection tasks in oil, gas, or sewage systems with minimal human intervention. In the field of search and rescue, soft-bodied robots are advantageous for penetrating debris-filled environments, such as collapsed buildings or rubble after natural disasters. Their ability to deform and squeeze through tight openings makes them ideal for locating trapped survivors or delivering communication and medical supplies in areas inaccessible to larger equipment. Their low impact forces also reduce the risk of causing further structural collapse or injury [15].

6. Challenges and Future Perspectives

In spite of significant progress, the worm like bionic robots are confronted with a number of critical challenges toward their practical maturity and wide application. The actuators are a bottleneck for many robotic systems, especially for untethered machines as the work here suggests. The majority of the soft actuators, however, either rely on large pumps (e.g. pneumatic chambers) and power sources with high volumes or is dependent on external controllers (e.g. shape memory alloys), thus compromising their autonomy and limits miniaturization. Compact, efficient and responsive actuators are still crucial for practical deployment in mobile and embedded scenarios. There are also considerable complications associated with integration of sensing and control. Soft robots tend to deform in a non-linear manner which can be difficult to model and track in real time. Incorporating strong and stretchable sensors that provide a reliable feedback without sacrificing flexibility remains a’ challenge. Furthermore, the control laws should also be robust with respect to unmodeled environmental disturbances, uncertain friction and morphological states [16]. From the material perspective, durability, self-repair ability, and biocompatibility, especially for medical and rescue situation, are open research frontier. Despite such level of development, the prior art materials are susceptible of fatiguing, tearing, or load deterioration when subjected to repeated stress or harsh environments. In the future, the field is trying to progress to multi-modal locomotion, in which the robots can change the body undulatory peristaltic or anchoring gait adaptively to the task requirements. This will be done in a co-designed fashion of structure, actuation, and control. Furthermore, breakthroughs in machine learning and adaptive control should significantly improve autonomy, allowing these robots to learn from experience and generalize to new terrains.

Ultimately, realizing the full potential of worm-like bionic robots will depend on cross-disciplinary innovations that fuse soft mechanics, smart materials, and intelligent systems design into robust and adaptable robotic platforms.

7. Conclusion

Worm-like bionic robots represent a compelling convergence of biological inspiration, advanced materials, and intelligent control. This review has synthesized the current state of the art in soft-bodied locomotion systems modeled after earthworms, nematodes, and inchworms, highlighting the mechanical and functional advantages of such designs in unstructured, constrained, or sensitive environments. Advances in actuation—especially pneumatic, hydraulic, and electroactive polymer-based systems—have enabled peristaltic and undulatory movement with increasing precision and adaptability. Structural innovations, such as modular segmentation and continuous soft bodies, combined with biologically inspired control schemes like Central Pattern Generators (CPGs) and reinforcement learning, have further expanded the capabilities of these robots across applications from pipeline inspection and medical endoscopy to search-and-rescue and underwater exploration. Nevertheless, several challenges limit the widespread deployment of worm-like soft robots. Key technical constraints include the trade-off between actuator power density and response speed, the lack of fully integrated soft sensors and compact energy sources, and the difficulty of achieving robust multimodal locomotion in variable terrains. Many current systems still rely on external power or control modules, hindering their autonomy and miniaturization. Furthermore, material fatigue, limited durability, and insufficient self-healing capabilities pose additional barriers to long-term or high-risk use, particularly in biomedical or disaster-relief scenarios.

While this review provides a comprehensive overview of worm-like bionic robots, several limitations must be acknowledged. The categorization and comparison of existing systems are constrained by inconsistent benchmarking metrics across studies, making it difficult to quantitatively evaluate performance in a unified framework. Future studies should aim to develop standardized testing environments and evaluation criteria to better compare locomotion efficiency, durability, and autonomy. Advances in bio-hybrid integration—such as embedding living tissues or synthetic bio-materials—may also unlock new performance regimes.

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