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Research of Bio-Inspired Motion Control in Robotics

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Abstract. Bio-inspired motion control in robotics draws inspiration from biological systems to enhance the movement capabilities of robots. This article explores the integration of bionics techniques in robots' path planning, motion control, and design of moving parts, offering advantages over traditional robots control systems. In path planning, bio-inspired approaches, such as swarm intelligence algorithms and artificial neural networks, optimize trajectories and enable obstacle avoid ability in complex environments. Furthermore, bio-inspired design principles facilitate the creation of motion components tailored for specific locomotion modes, such as legged locomotion and aquatic propulsion, improving robots' agility and adaptability. Reflex-based and vision-based control methods emulate biological responses and utilize visual sensors to enhance robots' perception and responsiveness. Additionally, recent advancements include the exploration of Long Short-Term Memory Networks (LSTM) for predicting control inputs based on animal trajectories. Through a synthesis of biomechanical principles, materials science, and artificial intelligence integration, bio-inspired motion control revolutionizes robotic capabilities, with implications for autonomous navigation and task execution in dynamic environments. Future research directions include further investigation into biomechanical principles, advancements in materials science, and the integration of artificial intelligence algorithms for enhanced autonomy and adaptability in robotics.

Keywords: Bionics; Swarm intelligence algorithms; Reflex-based control.

1. Introduction

In today's rapidly advancing era of technology, robotics is progressively moving towards intelligence and turning to applying bio-inspired techniques. Among these advancements, bio-inspired motion control in robotics has garnered significant attention. Drawing insights from biological systems, this technology offers innovative approaches to controlling robot movement. Traditional methods of robot path planning and motion control have certain limitations due to their nature of static and deterministic. These methods often rely on fixed algorithms and strategies, which lack the flexibility to adapt to complicated and constantly changing environments. Additionally, conventional robots may have limited sensory perception capabilities, leading to difficulties in accurately perceiving and interpreting complex environmental cues. Compared to traditional computer-programmed systems, bio-inspired motion control methods can avoid these limitations, and confers several advantages, including enhanced robustness, agility, and adaptability.

Path planning stands as a crucial aspect in robotics, involving determining the optimal route for robots in different environments, and giving robots ability to effectively avoid obstacles. In recent years, bio-inspired approaches to path planning have gained prominence due to their ability of tackling challenges in complex and dynamic environments. By emulating behaviors observed in biological systems, such as the collective intelligence of ant colonies, techniques like ant colony optimization facilitate autonomous navigation in diverse environments.

Furthermore, bio-inspired design of motion components plays a pivotal role in optimizing robot locomotion. Inspired by organisms' locomotive appendages, robots' moving components can be tailored for specific movement modes, and therefore enhancing efficiency and adaptability.

Bio-inspired approach also provides new solutions for robots' motion control methods, scientists mimic the creatures' motion control system, like vision-based control and reflex control of animals.

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By doing this, this paper can find simpler and easier solution to give robots a certain level of intelligence for its movement.

Therefore, this article explores the research progress and potential applications of bio-inspired motion control in robotics. By harnessing insights from biological systems, this paper can develop more adaptable and flexible motion control strategies for robots, paving the way for new direct.

2. Three aspects of Bio-Inspired technology application in robotic motion control

Bio-inspired motion control in robotics draws inspiration from biological systems to develop innovative approaches for controlling the movement of robots, and it have several advantages compared with generic computer-programmed robot motion control system. By using bionics techniques in robots' path planning, motion control, or bionic design of moving parts, robots may have robustness, and higher agility and flexibility.

2.1. Bio-inspired techniques in robot's path planning

Path planning is a fundamental aspect of robotics, involves determining the optimal route for a robot to navigate from its current position to a specified goal location while avoiding obstacles and optimizing various objectives. In recent years, bio-inspired approaches to path planning have gained considerable attention due to their ability to address challenges encountered in complex and dynamic environments.

Bio-inspired techniques help autonomous mobile robots to solve the problem of giving the robot the ability to autonomously accomplish path planing in different environment. For example, swarm intelligence can help the robot to find the shortest path by emulate the behavior of ants' colonies when they are looking for food (Fig. 1), and optimize the search of the shortest path by using ant colony optimizations (ACO) [1]. Swarm intelligence refers to the collective behavior of decentralized, self-organized systems, inspired by the coordination and collaboration observed in natural swarms, to solve complex problems and optimize tasks, is valuable to be applied in robots' path planning. Ant Colony Optimization (ACO) is a stochastic, distributed and collective approach that has been used to solve different hard combinatorial optimization problems [2].

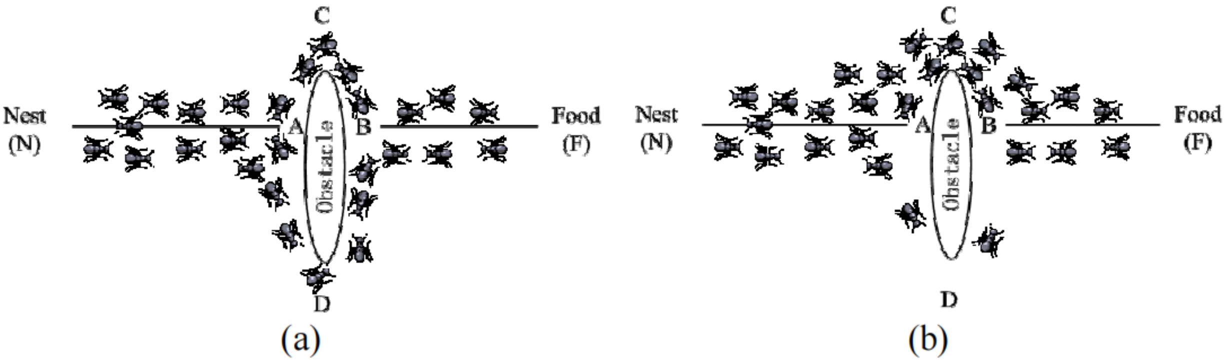

Fig.1 (a) Ants choose their path in a probabilistic way. (b) After certain time, the density of pheromone is higher in the shortest path and this causes that ants choose the shortest path [1].

Besides finding the shortest path, bio-inspired techniques also help robots to detect and avoid obstacles through improved path planning algorithm, like firefly algorithm and Artificial Bee Colony (ABC), Firefly algorithm, first developed by Xin-She Yang in late 2007 and 2008, is a nature-inspired optimization algorithm that mimics the flashing behavior of fireflies to search for optimal solutions in optimization problems. It followed three idealised rules: Fireflies are unisex so that one firefly will be attracted to other fireflies regardless of their sex, The attractiveness is proportional to the brightness, and they both decrease as the landscape of the objective function determines their distance increases, and the brightness of a firefly [3]. Artificial Bee Colony (ABC) is a population-based optimization technique inspired by the foraging behavior of honey bees. In ABC, a colony of artificial bees iteratively searches for the optimal solution to a given problem by mimicking the foraging behavior of real bees. The algorithm consists of three main components: employed bees, onlooker bees, and scout bees. Employed bees explore the search space around the known food sources, while onlooker bees select their search areas based on the information gathered from employed bees. Scout bees are responsible for randomly exploring new areas when the employed and onlooker bees fail to find better solutions. These two algorithms have been utilized in robot path planning tasks to optimize trajectories, avoid obstacles, and improve overall navigation efficiency in complex environments.

Also, recent advancements in robotics have led to the first-time exploration of Long short-term memory Networks (LSTM) as potential planners for bio-inspired robotic motion. In this study, they train an LSTM network to learn temporal dependencies in a given set of animal trajectories, and with A total of 100 datasets of fish trajectories were simulated, each having 6000 iterations, the results shows that the LSTM-based model exhibits strong predictive capabilities for control inputs in bio-inspired robotic motion, even amidst varied environmental conditions [4].

2.2. The bio-inspired design of robotic motion components.

Robotic motion component design, drawing inspiration from nature's biomechanics can enhance versatility and efficiency of robots by enabling tailored locomotion modes for specific tasks. The design of robotic motion components is very important in robots' motion control, and it is pivotal in achieving specific locomotion modes tailored to the intended application. Drawing inspiration from nature, such as the biomechanics of animals or insects, allows for the creation of motion components optimized for particular modes of movement. By mimicking the anatomical structures and motion patterns of biological organisms, robotic components can be engineered to excel in certain activities like crawling, walking, swimming, or flying. For instance, legged locomotion can be facilitated by articulated joints and actuator systems that replicate the flexibility and coordination observed in animals. One most published compliant legged robot is by drawing inspiration from the locomotion of running animals, the roles of the elastic elements have been implemented in fast running (or hopping) robots with various forms in order to improve their dynamic performances (Fig. 2) [5]. Also, by researching the musculoskeletal functions of the human leg as well as of its control structure, scientists can achieve elasticity for bio-inspired bipedal robots, which is an essential property necessary to achieve versatile and energy-efficient motions [6].

Fig.2 Biped 'Lucy'[5]

Drawing inspiration from aquatic creatures, fin-like fins in robotics revolutionize underwater motion control, enhancing maneuverability and efficiency through biomimetic design principles. Fin-like fins or fin-like limbs represent another pivotal facet in the realm of bio-inspired motion control in robotics. Leveraging principles derived from nature, these biomimetic technologies aim to revolutionize the design of robotic motion components, particularly in underwater environments. By emulating the hydrodynamic efficiency and agility observed in fish propulsion, researchers endeavor to enhance the maneuverability and efficiency of underwater robotic systems. Through a synthesis of biomechanical studies on fish locomotion and advancements in robotics, fin-like fins offer promise in augmenting the capabilities of underwater robots for tasks ranging from environmental monitoring to underwater exploration and surveillance. Thus, the integration of fin-like fins exemplifies a burgeoning frontier in the application of bio-inspired principles to propel advancements in robotic motion control. Aquatic locomotion may require propulsive mechanisms resembling fins or flippers for efficient underwater navigation. For instance, undulatory fin propulsion, inspired by the locomotion of aquatic species such as electric eels and cuttlefish, holds considerable potential for endowing underwater vehicles with enhanced propulsion and maneuvering abilities, to address the needs of a growing number of applications [7]. By replicating the undulating movement of natural fins, this approach helps underwater robots or underwater detect vehicles to navigate through water with enhanced agility and efficiency. It has promising future using in areas like marine exploration, underwater surveillance, and environmental monitoring, where precise control and maneuverability are crucial.

The bio-inspired design of robotic motion components revolutionizes robotic motion control, enriching theory and practice. It offers insights into biological principles, enhances robot performance, and improves adaptability in dynamic environments, is a vital area in bio-inspired motion control. In the future, research in bio-inspired design of robots is expected to focus on several key directions. Firstly, there is a need for further investigation into the biomechanics and neuromechanics of biological systems to uncover underlying principles that can be translated into robotic designs. Additionally, advancements in materials science and fabrication techniques will enable the development of more sophisticated and biologically-inspired robotic components. Furthermore, integrating artificial intelligence and machine learning algorithms with bio-inspired designs will enhance the autonomy and adaptability of robotic systems, allowing them to navigate diverse environments and perform complex tasks more effectively.

2.3. Bio-inspired motion control methods in robots

Using bio-inspired techniques in robots' motion control method helps robots to leverage principles from biomechanics, neuroscience, and control theory to develop robotic motion control strategies that mimic or surpass the agility, adaptability, and efficiency observed in nature. Compared with bio-inspired design of robotic motion components, which primarily focuses on the structural and mechanical aspects of robotic systems, bio-inspired motion control methods delve deeper into the dynamic regulation of movement, encompassing sensory-motor coordination, feedback mechanisms, and adaptive behaviors. While both fields draw inspiration from biological systems, and it have similar concepts, bio-inspired motion control methods prioritize the development of algorithms and control strategies that enable robots to navigate and interact with their environment in a biomimetic manner.

Vision-based control method is one typical bio-inspired motion control methods, which refers to the utilization of visual sensors and image processing techniques in the field of bio-inspired robotics to enable robots to perceive and understand their surroundings, facilitating motion control. Marvelous vision-based dynamic behaviors of insects and birds such as perching, landing, and obstacle avoidance have inspired scientists to propose the idea of time-to-contact, which a concept inspired by the dynamic behaviors observed in insects and birds, such as perching, landing, and obstacle avoidance. It represents the time it takes for a moving observer (such as a robot) to come into contact with an object or surface if it maintains its current velocity. Since with only a vision sensor, time-to-contact can be directly estimated from consecutive images. It is widely used by a variety of robots to fulfill various tasks such as obstacle avoidance, docking, chasing, perching, and landing [8]. Vision-based control methods have diverse applications. In industry, Vision-based control robots are extensively utilized in automated assembly lines and manufacturing processes. They employ vision sensors to detect and locate components, enabling tasks such as automated assembly, quality inspection, and material handling. In agriculture, vision-based control robots automate farming tasks such as planting, weeding, spraying pesticides, and harvesting. However, this kind of robots is still not ready for wide-ranging practical application. Although harvesting robot holds ample promise for the future, currently the overall performance of harvesting robot is often insufficient to compete with manual operation (Grift et al., 2008). The bottleneck to promote the application of harvesting robot lies on the performance of vision-based control [9].

Reflex-based control methods, inspired by the rapid and automatic responses observed in biological organisms, have garnered significant interest in robotics. These methods emulate the simple yet effective stimulus-response mechanisms found in living organisms, enabling robots to react swiftly to sensory inputs without the need for complex cognitive processing. In the realm of robotics, reflex-based control techniques are increasingly being explored to enhance the agility and responsiveness of robotic systems, especially in dynamic and uncertain environments. Reflex-based control methods can also help with programming errors. As higher-level software becomes more complex, the likelihood of unsuspected, embedded programming errors becomes high. To protect against such errors, only completely trustworthy low-level software can be depended on. By analogy, this low-level software is referred to as reflex control, since this software invokes reactions which are responsive to sensory input and are appropriate for preserving viability, yet are not complex enough to be labeled as 'intelligent' [10]. Also, researchers are actively investigating novel algorithms and architectures to improve the robustness and adaptability of reflex-based control methods, aiming to address challenges such as real-time decision-making, obstacle avoidance, and interaction with dynamic surroundings. By leveraging the principles of reflexive behavior, these methods hold promise for advancing the capabilities of robots in various domains, including autonomous navigation, human-robot collaboration, and task execution in unstructured environments.

By mimicking specific movement patterns of humans and other organisms, this paper may achieve the goal of protecting the robot while it's moving and achieve improved robot motion performance and adaptability. This control approach helps robots achieve safer and more natural motion, enabling better adaptation to complex environments and task requirements. Scientists increase the safety of Biped Humanoid Robot while it's moving by imitating the motion of human knees during falls. By studying four strategies based on human protective falling motion: "knee flexion", "torso flexion forward", "torso translation backward" and "knee stretched", this paper can achieve a safe falling motion control method (Fig. 3) [11]. Also, reflex-based control method can protect robots by minimize the responding time, for example, reflex-based control systems are integrated into the navigation systems of some autonomous vehicles to detect and helps vehicles to respond quickly to unexpected obstacles on the road. In manufacturing environments, industrial robots equipped with reflex-based control mechanisms can quickly respond to changes and accidents. If a sensor detects a human operator entering a restricted area, the robot can immediately halt its operations to prevent potential accidents.

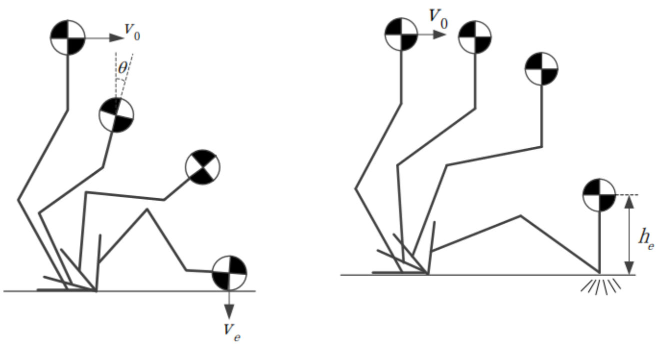

Fig. 3 Stick figure of strategies (a) Knee flexion strategy (b) Torso flexion forward strategy [11]

Bio-inspired motion control in robotics integrates principles from biological systems to develop innovative approaches for controlling robot movement, offering advantages over traditional control systems. By incorporating bionics techniques into robots' path planning, motion control, and design of moving parts, robots gain robustness, agility, and adaptability. Bio-inspired path planning methods, like swarm intelligence algorithms, optimize trajectories and obstacle avoidance. Biomimetic design principles enable the creation of motion components tailored for specific locomotion modes. Reflex-based and vision-based control methods emulate biological responses and utilize visual sensors, enhancing robots' agility and perception. Overall, bio-inspired motion control revolutionizes robotic capabilities, with future research focusing on biomechanical principles, materials science, and artificial intelligence integration for enhanced autonomy and adaptability.

3. Conclusion

The exploration and integration of bio-inspired motion control techniques within the field of robotics has already yielded significant advancements and potential applications. It is revolutionizing robots' motion control by harnessing principles from natural systems to enhance robot movement. Applying bio-inspired methods in robots' motion control generally has four big advantages. Firstly, it enhanced agility and efficiency of robots, by using bio-inspired algorithms, which offer superior robustness, global optimization, parallelism, adaptability, and innovative problem-solving. It helps robots to be excelled in complex, dynamic environments, leveraging principles from biological systems to adapt and evolve strategies efficiently. Secondly, it offers robots adaptability to dynamic environments. Biomimetic design principles allow for the creation of motion components tailored for specific locomotion modes, like fin-like motion components for swimming. This enhanced robots' ability to adapt to diverse and dynamic environments. Thirdly, bio-inspired methods can improve perception and responsiveness of robots. For example, vision-based control method enhances robotic perception and responsiveness by utilizing images from cameras or other visual sensors, these methods enable robots to perceive and understand their surrounding environment in real-time. This capability allows robots to accurately detect obstacles, recognize objects, and navigate through complex surroundings with greater precision. Reflex-based control methods enhance robotic perception and responsiveness by emulating rapid automatic responses observed in biological organisms. These methods enable robots to react swiftly to sensory inputs without complex cognitive processing, and offering robots the ability to better adjust to unknown environments. Finally, it gives robots robustness and versatility. By leveraging principles from biological systems, bio-inspired motion control methods enhance the robustness and versatility of robotic systems, enabling them to perform a wide range of tasks with precision and reliability.

In light of these developments, the continued exploration and refinement of bio-inspired motion control methodologies hold immense promise for shaping the future of robotics. Future research endeavors should focus on further elucidating the underlying principles of biological systems, advancing materials science and fabrication techniques, and integrating artificial intelligence algorithms to enhance the autonomy, adaptability, and efficiency of robotic systems. By leveraging the inherent efficiency and adaptability of biological systems, bio-inspired motion control stands poised to totallyrevolutionize robotics technology.

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